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EFFECTS OF TRAINING, HEAD MOVEMENT, ELEVATION, AND AZIMUTH ON SOUND LOCALIZATION IN MONAURAL AND BINAURAL HUMANS.

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EFFECTS OF TRAINING, HEAD MOVEMENT, ELEVATION, AND AZIMUTH ON SOUND LOCALIZATION IN MONAURAL AND BINAURAL HUMANS

(C)

by

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ABSTRACT

The effects of (a) pretest training (two levels: training, no-training), (b) stimulus elevation ($0, \pm30^{\circ}$), (c) stimulus azimuthal angle ($30, 60, 90, \ldots 0^{\circ}$), and (d) head movement (head rotate, head fixed) on the accuracy of monaural versus binaural directional hearing were examined using 72 university students tested in a mixed design experiment having stimulus azimuthal angle and head movement as the within-block treatments. The blindfolded subject sitting at the center of a clock face marked out on the floor of a sound-proofed room was required to verbally indicate using the clock numbers the direction of a 2 second pulsed white noise stimulus. Analyses of the second and third-order interactions revealed the following: (a) On their occluded side, untrained and head fixed monaural listeners were clearly inferior to binaurals; however, on their non-occluded side their performance often matched that of binaurals. (b) Binaural listeners free to rotate their heads had the smallest error scores, and these scores were independent of azimuth. (c) For binaural listeners, fixing the head produced a considerable increase in the size of errors in the rear quadrant, but not elsewhere, and this trend was influenced by elevation. No similar rear quadrant error size increase was noted for monaurals. (d) Localization accuracy for monaurals and binaurals was usually improved with head rotation. However, at some azimuths, for example, opposite the non-occluded ear for monaurals and in the frontal region for binaurals, accuracy decreased for the head rotate condition. (e) Training monaural

listeners increased their accuracy on the occluded ear side, but had a nonsignificant influence at the remaining azimuths. For binaurals, however, training made no significant improvement in the accuracy in any quadrant. And (f) contrary to previous findings, monaurals made significantly more front-back reversals than binaurals. It was concluded that accurate sound localization depends on the interaction of a number of factors and, therefore, the manipulation of variables and the design of studies should reflect this interrelationship.

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Chapter I

Introduction

Historians suggest that around the end of the eighteenth century man began empirical research examining how sounds are localized in space. Venturi's work (1800a, 1800b) suggested one important cue for two ear, directional hearing, i.e., interaural intensity difference, and by the beginning of the twentieth century, two additional physical cues, dichotic phase (Dove, 1857) and dichotic time (Mallock, 1908) had also been hypothesized. Typically, dichotic refers to the condition where the stimulus presented to one ear differs in some way, e.g., time of presentation or phase relationship, from that to the second ear. But in other respects the two stimuli are identical, i.e., diotic.

About this time work on single ear localization was also reported. Along with the early findings (e.g., Angell & Fite, 1901; Klemm, 1918), indicating that monaural patients could still perceive sound direction, came a growing interest in the accuracy of these perceptions. If monaural localization could be precise, then the traditional assumption that sound localization required binaural input needed qualification. Angell & Fite (1901) suggested how monaural mechanisms might work; but it was Batteau's (1961, 1967) pinna reflections theory and research which persuaded many workers of the existence of a monaural system for sound localization.

Studies showing that monaurals can perform as well as normals and under what circumstances have appeared infrequently compared to those theorizing on monaural mechanisms (e.g., Bloom, 1977; Freedman & Fisher, 1968; Roffler & Butler, 1968; Searle, Braida, Cuddy & Davis, 1975; Wright, Hebrank & Wilson, 1974) or those illustrating the sound transformation characteristics of the pinna (e.g. Blauert, 1969/70; Mehrgardt & Mellert, 1977; Shaw, 1974; Wiener, 1947; Wiener & Ross, 1946). In his review of the literature, Gatehouse (1969) concluded there was no general agreement that monaural localization could be as accurate as binaural. Although some careful research (e.g., Fisher & Freedman, 1968a; Gatehouse & Cox, 1972; Hebrank & Wright, 1974a; Perrott & Elfner, 1968) has shown that under certain conditions monaurals can perform as well as normals, if not better (Fisher & Freedman, 1968a), few researchers have sought to identify and manipulate more of these conditions. That all such variables should be isolated and systematically varied is suggested by the inconsistent findings often reported for monaural versus binaural accuracy on vertical and horizontal tasks. For example, Fisher and Freedman (1968a) and Perrott and Elfner (1968) reported monaural, horizontal plane localization could be as accurate as binaural; whereas, Batteau (1968), Gatehouse and Cox (1972), and Russell (1976) found monaurals were clearly inferior on the task. Similar discrepancies have occurred for vertical localization. Butler (1969b), Gardner (1973b), and Butler and Planert (1976) found monaurals were less accurate than binaurals while Bothe and Elfner (1972), Gatehouse and Cox (1972), and Hebrank and Wright (1974a) reported no differences. In some of these studies, e.g., Perrott & Elfner (1968); Hebrank & Wright (1974a), the authors did suggest that feedback training was necessary before monaural performance approached binaural; in others, however, (e.g., Russell, 1976) little or no discussion was given to the influence of training or of other factors such as stimulus duration, speaker span (Searle, Braida, Davis, & Colburn, 1976), elevation and azimuth of stimulus source, visual cues and head position (see Harris & Sergeant, 1971 for a more exhaustive list)--factors, some of which, as the review to follow will indicate, either are known to influence localization accuracy or may have that potential. The purpose of the present study was to examine, using a factorial design, the influence of four of these variables which have frequently, as extraneous variables, been allowed to go uncontrolled, or if controlled, to assume different levels across studies. By building these four variables into the design, it was hoped (1) that some of the inconsistencies in the localization literature cited above would be resolved by isolating an interaction(s) between an original independent variable (i.e., monaural or binaural directional hearing) and the former extraneous variable (see McGuigan, 1968, pages 275-277; and Christensen, 1977, pages 131-132 on this assumption) and (2) that the data obtained would be useful for modeling attempts such as that of Searle et al. (1976).

Specifically, the problem to be considered was as follows: What are the independent and interactive effects of (1) stimulus azimuthal angle, (2) stimulus elevation, (3) pretest training, and (4) head movement on the accuracy of monaural versus binaural directional hearing?

Historical Review

Because the above four variables were manipulated in order to influence the usefulness of the several physical cues used for directional hearing, the review will (1) outline the research which has suggested what these cues are, (2) discuss factors known to influence these cues, (3) illustrate how the methodology of those studies that either support or question the reported accuracy of a second directional hearing system, one based on monaural physical cues, do not control the same extraneous variables and thus may contradict one another for that reason, and finally (4) draw on the preceding aims to provide the rationale for a series of hypotheses that were tested in this study.

The review will develop under four main headings: (1) Binaural Cue System, (2) Monaural Cue System, (3) Horizontal Localization: Monaural versus Binaural, and (4) Vertical Localization: Monaural versus Binaural. The leitmotif throughout the first two sections is based on a scheme for evaluating potential localization cues reported by Coleman (1963) and used to advantage by Searle, Braida, Cuddy, and Davis (1975). Coleman studied distance judgment in auditory space, but the scheme's usefulness for vertical and horizontal localization is obvious from the following:

> Although physical acoustics can point out the existence of information that may provide the basis for several possible cues to auditory distance, it rests with psychophysics to show (a) that this information can be detected by the ear, and (b) that it is utilized in arriving at distance judgments.

Although, as this quote implies, auditory distance perception should be considered in discussing localization, it typically is not. And in the relatively few studies (see Mershon & King, 1975 for references) which have examined distance judgment, none refer to a monaural versus binaural comparison. For the purposes of this review then localization will mean the perceptual referral of a stimulus source to a point in one, two, or three-space (i.e., front-back; up, down; left, right), without regard to distance.

Binaural Cue System

Three basic cues. During the nineteenth century the underlying concern of auditory researchers was not - can the organism discriminate between relative positions of tones? and if so, how? but rather, how do non-spatial tones get placed in space? a so-called genetic problem (Boring, 1942). By denying that tones could have spatial magnitude, the nineteenth century psychologists were then obligated to question the existence of a solely auditory space perception, a position which led to an unproductive search into the role of touch and kinesthesis in providing spatiality to tones.

But this was not the only false lead. On the basis of his work, Helmholtz declared that we cannot detect phase. This was an unfortunate conclusion, and it, along with the belief that tones lack spatial magnitude, acted to hinder the dissemination of experimental findings contrary to these beliefs (Boring, 1942). It should be made clear, however, in fairness to Helmholtz that he was misunderstood and did, in fact, believe that phase could probably be detected (Stevens, 1962). Unfortunately, it was not that view which influenced the pioneers in auditory research.

This was the Zeitgeist, then, which touched many of the nineteenth and early twentieth century researchers and which played a part in delaying an explanation of the basic binaural cue system--interaural amplitude, phase, and time differences--over 130 years until Trimble (1928) reviewed the localization literature and speculated on its implications.

It was Venturi's (1800a, 1800b) work which provided the first clue as to how that system functioned. Venturi is not usually given credit for being the first to postulate the existence of a major interaural difference cue, i.e., intensity disparity--which according to Kuhn (1977) is more correctly called sound pressure level difference --although he went to some effort to inform the scientific community of his hypothesis (Rosenzweig, 1961). The theory was based on experiments which he performed outdoors in an open field, a location which because of the low level of ambient noise existing in the world of the late eighteenth century, and because of the lack of sound reflecting and diffracting surfaces was ideal for localization studies. Typically, Venturi would circle a subject, who had either normal hearing or a severe loss in one ear, at 40 meters while playing occasional notes on his flute, the subject's task being to indicate the direction of the tones (Gulick, 1971). From such studies, Venturi concluded that it is the simultaneous difference in intensity at the two ears that informs the listener of the position of a sound. That is, when a sound is heard off to one side of the head, it will appear louder to the ear on that side. The theory was used to explain why, without head movements, listeners made front-back errors when the stimulus was located either at zero degrees azimuth or 180 degrees, and why monaurals had difficulty localizing unless allowed to move their heads. In the former case Venturi felt that these azimuthal positions provide equal intensity levels to the two ears, thus confusing the listener; while in the latter case there is no second ear to detect the loudness gradient.

The intensity hypothesis gained wide acceptance during the next seventy-five years. Magendie (1831) supported it, as did Müller (1840) who developed the idea further. He supposed that a listener determines the position of a sound by consciously judging the intensity difference at his or her two ears. Known as the judgmental hypothesis, this proposal caused some controversy until von Hornbostel (1926), whose research will be discussed later, convincingly showed the fallacy of the hypothesis.

Seventy-five years after Venturi's studies, Lord Rayleigh (J. W. Strutt) reported some very similar research (Rayleigh, 1876). While standing on a lawn and surrounded by a circle of assistants, Rayleigh with eyes closed attempted to localize the assistants' positions as they individually spoke to him. Although he was accurate to within a few degrees when localizing voices, he reported that low pitched tuning forks (150 Hz and less) caused some difficulty. He attempted to explain these results by suggesting that for high tones intensity differences at the two ears would be relatively large, they would be smaller for lower frequencies, and almost negligible for tones whose wavelengths were four times the diameter of the head.

In the following year, Rayleigh (1877) conducted additional experiments using pure tone stimuli and drew the conclusion that localization depends on the ratio of the sound intensities at the listener's two ears, a relationship which is referred to as the binaural ratio--meaning simply a ratio of intensities. He also pointed out that no sound has a unique ratio. A stimulus in a front lateral position produces the same intensity differences at the two ears as an identical sound located at the same locus in the back lateral field.

Because of this, listeners can confuse sounds positioned to one side, much as they do sounds located directly in front or behind.

All together, Rayleigh demonstrated five characteristics of sound localization with his experiments: (1) voices are more accurately localized than tones, (2) high tones are better localized than low, (3) the binaural ratio is important for localization, (4) laterally located stimuli can cause front-back confusion, and (5) listeners do not confuse a sound on the left from one on the right. With the exception of point (2), which Stevens and Newman (1936) later showed to be incorrect, these conclusions have proven to be accurate.

Further support for the intensity theory came from Von Kries and Auerbach (1877), Thompson (1878), Tarchanow (1878) and Urbantschitsch (1881), all of whose work is briefly summarized by Boring (1942). The reports of Tarchanow and Urbantschitsch are interesting. Their research showed that when two telephone receivers, located one on either side of the listener, delivered stimuli diotic with respect to intensity, the listener perceived a single sound in the median plane. As the stimuli were made increasingly dichotic, the position of the phantom moved toward the side receiving the louder stimulus, a convincing demonstration of the influence of Lord Rayleigh's binaural ratio as a factor in auditory localization.

Although it would be of interest to review more of these studies (see Pierce, 1901, for reports supporting the intensity hypothesis--e.g., Bloch, 1893; Matsumoto, 1897; Smith, 1892; Thompson, 1882; von Bezold, 1890) it is sufficient for present purposes to have illustrated that interaural sound pressure level difference was an accepted localization cue at the turn of the century. This was not the case, however, with the two remaining cues: phase and time disparity. Phase was not an accepted cue owing to Helmholtz's dictum that it could not be perceived; and time differences had not yet been suggested.

Rosenzweig (1961) argued that Dove (1857) was the first to seriously consider the role of dichotic phase differences in auditory localization, but Rosenzweig supplies no details on the paper. Both Boring (1942) and Gulick (1971) fail to mention Dove, citing Thompson (1878) instead as being the first to advance a phase hypothesis. Because summaries of Thompson's work are readily available, his research will be considered here.

Thompson (1877) reported that when the sounds from two tuning forks, one 256, the other 512 Hz, were simultaneously conducted through a single tube which branched to each ear (a stethoscope-like apparatus used in most of these early studies examining phase), he could change the phase relationships by rotating one of the forks about its axis and cause the sound of the rotated fork to migrate from the front to the rear in the listener's head while the sound of the second fork remained fixed. He could also produce the same effect by picking up the vibrations of each tuning fork on a separate telephone receiver and then leading the two sounds to the input tube of the ear pipes. By reversing the phase of one of the receivers electrically, he was able to cause the same migration of the sound as before. Unfortunately, the results of these experiments were not accepted at the time owing to the suspicion that phase changes were not detectable.

Thirty years later, Lord Rayleigh (1907) outlined his phase theory to a more receptive audience. Rayleigh found that when two

128 Hz tuning forks were struck in separate rooms and the resulting tones conducted by separate tubes to the ears of a listener in a third room, the listener received the impression of the tone moving from one side of his or her head to the other. When the effect was at its best, the sound appeared to lie entirely to the right or left. It seemed apparent to Rayleigh that the changing phase relationship of the two forks caused the sound's migration through the head, with the side leading in phase having the image. He obtained similar results using forks up to 768 Hz but cautiously limited the phase effect to frequencies below 256 Hz, frequencies which he felt could not theoretically produce detectable intensity differences between the two ears. As a general conclusion, Rayleigh suggested that low tones are localized using phase differences and high tones using intensity, an insight which foreshadowed the duplexity theory.

Following Rayleigh's publication, More and Fry (1907) reported results they had obtained five years earlier but declined to publish because of the bias toward phase effects. Their sound presentation apparatus consisted of a hollow tube which branched off to each ear, with one of the branches having a slide extension which could be used to alter the length of the tube on that side. By introducing the sound of either a 512 or 320 Hz tuning fork into the opening of the tube and varying the length of the extension, More and Fry were able to create the impression in a listener that the tone was shifting from side to side in his head.

Wilson and Myers (1908) repeated these experiments but more thoroughly. Rather than use a slide in one branch of the tube, they joined the two branches from each ear to the horizontal ends of a hollow, T-shaped metal pipe. With the tubes held in place, the pipe could be moved to the left or right, effectively lengthening or shortening the path lengths of the ear tubes. When the tone of either a 320 or 512 Hz tuning fork was introduced into the vertical opening of the pipe and the pipe was then moved in a systematic fashion back and forth along a graduated scale, a listener received the impression of the tone moving to the side leading in phase, the effect occurring up to a phase angle limit of 180°. Surprisingly, Wilson and Myers concluded that although binaural differences in phase were the primary cause of these lateral effects, the ultimate cause was an interaural difference in intensity. The influence of Helmholtz was apparently still being felt.

Wilson and Myers' conclusion notwithstanding phase differences were now generally recognized as a cue for localizing low frequencies.

It was also at this time that a third cue, interaural time disparity, was reported. Here, as with the phase cue, there is some uncertainty regarding who initially reported the utility of time differences. Rosenzweig (1961) and Gulick (1971) suggest Mallock (1908) was the first to seriously propose a time hypothesis, i.e., dichotic time provides a basis for localization, and Aggazzotti (1911) the first to demonstrate it experimentally, although neither Rosenzweig nor Gulick provides any details on these papers. Boring (1942), however, cites von Hornbostel and Wertheimer (1920) and Klemm (1920) as the initiators of the hypothesis, and owing to the availability of summaries on these reports, the discussion will begin with them.

Because these studies and others manipulating interaural time difference cues use a similar experimental paradigm, a general description of it will be given now to avoid repetition. Woodworth and Schlosberg (1954) give the following description:

> The telephone dichotic apparatus uses earphones, each having a separate circuit with amplifiers or attenuators to control intensity, and with adjustable condensors to produce a binaural time difference. The source for both ears is an oscillator producing tones of known frequencies, the frequency always being the same for both ears. The composition of the sound wave, its overtone structure, can be controlled to some extent by sound filters and other means. Clicks at any desired time difference can be produced in the earphones by an adjustable contact apparatus which interrupts the circuits through the two telephones. The two earphones must be carefully selected to secure clicks of the same quality which will fuse and be heard as a single click when presented simultaneously to the two ears. (page 354)

Using this arrangement, von Hornbostel and Wertheimer (1920) reported that clicks diotic with respect to time and intensity produced a single sensation in the center of the listener's head. As the two clicks were made dichotic with respect to time, the locus of the sound started to migrate from mid-line toward the earlier stimulus when the clicks were separated by about 30 μsec. With further increases in the time difference, the sensation migrated closer to the leading side until it became anchored there at approximately 630 μsec.

Klemm (1920) independently reported a similar but more surprising result. He found that the sound could be moved from mid-line with an interval between clicks of only 2 μsec. He also noted that at approximately 2 msec the completely lateralized sound broke into two successive clicks, one heard on each side.

These two experiments helped to establish interaural time difference as the third major cue in sound localization, but they were also relevant to two other issues. First, the fact that over 2 msec was required before listeners could judge two clicks as successive suggested that Müller's (1840) judgmental hypothesis of localization could clearly not be supported (Rosenzweig, 1961). Movements of the sound from the median plane occurred at values below the threshold for discriminating successive clicks, with the listener having no sensation of comparing two perceptual events. Second, the studies were also relevant to an issue that had generated considerable interest: Which cue is more important, intensity, time, or phase?

In the 1920 experiment, von Hornbostel and Wertheimer performed a balancing study indicating that time was more relevant. When the sound was lateralized at the left ear owing to a time delay between clicks of 100 μsec favoring the left side, they found the intensity to the right ear had to be raised considerably above the left to move the sound back to the centre of the listener's head. This suggested that a small interaural time difference was more potent than a large opposing intensity difference.

Klemm's (1920) work suggested otherwise. When the sound was lateralized to say the left ear by increasing the intensity to that side by a factor of three compared to the right, he found that the right ear had to receive the stimulus 600 μsec earlier than the left to bring the sensation back to mid-line. Because this is a relatively large time difference, the role of intensity could not be viewed as secondary.

Wittmann (1925) replicated these two balancing experiments and drew the reasonable conclusion that both time and intensity disparities should be considered effective cues in sound localization.

Trimble (1928) expanded on this conclusion when he attempted to integrate the three cues into a system where each would have a role. His paper had a familiar theme: "In a complex of sound, does either phase, time, or intensity predominate in determining the directional localization; or are all of these factors reducible to some common factor; or do they each and all contribute to a pattern of effects that results in directional perception?" (page 519). He considered the views of six researchers on the question: Klemm (1920) suggested that a time difference may be reducible to an intensity difference. Von Hornbostel and Wertheimer (1920) argued that phase difference is a special case of time difference, and that intensity is an inadequate cue for localization. Hecht (1922) agreed with Lord Rayleigh (1907) that intensity is the relevant cue for high frequencies, and phase for low with phase, time, and intensity all being germane for complex sounds. In Halverson's view (1922) phase, time, and intensity might be reducible to some common factor, although he didn't speculate what this would be. For Stewart (1925) both phase and intensity disparities were relevant, with phase being the more important of the two. And finally Boring (1926) agreed with von Hornbostel and Wertheimer (1920) that phase difference is a special case of time difference, but felt a time or phase difference is reduced to an intensity difference in the nervous system.

Trimble concluded that arguments similar to those of Rayleigh and Hecht best explained pure tone localization: dichotic phase is the potent factor in localizing low tones and dichotic intensity for high, a theory which is typically referred to as the duplicity or duplexity theory of sound localization. On the issue of complex sounds, Trimble hypothesized that all three cues, and possibly a fourth, which he referred to as mass, contribute to the difference-pattern which results in perceived direction. More specifically, he suggested that each cue contributed to the pattern in varying amounts depending on the locus of the sound source. Although Trimble gave no specific examples, he proposed that in some instances phase would add more to the pattern than any of the remaining cues, although in a different situation perhaps intensity would be the prime factor.

This scheme proved generally acceptable to auditory researchers when it was presented (Boring, 1942) and has remained the basis of modern localization theory. The fourth cue alluded to, mass--more commonly known as interaural spectral difference--has, during the last decade, become an exciting and controversial research topic. In the 1930's, however, it was not an established cue, but as a section devoted to its discussion later in the review will suggest, spectral disparity may be the most important signal for localizing the complex sounds of our natural environment.

Earlier it was suggested that to establish the utility of a localization cue, three factors proposed by Coleman (1962) should be considered: (1) a physical cue exists, (2) the organism can detect it, and (3) the organism uses the cue. Since the late 1920's, a number of studies either directly testing the duplexity theory or having relevance to it have been reported which fit conveniently into this scheme, their results supporting the theory and thereby giving credence to the less rigorous research on which it was based.

One issue should be clarified, however, before these studies are reviewed. That is, the relationship between time and phase in the duplexity theory. Because the theory refers to only two cues, typically time and intensity, the role of the third is left in question. Two studies reviewed in Trimble's (1928) paper (von Hornbostel and Wertheimer, 1920; Boring, 1926) suggested that phase difference is but a special case of time difference. This approach agrees with a recent statement by Searle (1978) in which he referred to phase shifts as a sub-category of interaural time difference. Brown, Beecher, Moody, and Stebbins (1978) hold a similar view, suggesting that a temporal disparity at the ears can be characterized as an interaural time delay or an interaural difference in the phase of the waveforms. It appears, then, that for pure tones a temporal difference between the left and right ear stimuli can be referred to as a time or phase difference. Erulkar (1972) has included this position in his summary of the general case: "Temporal cues may be in the form of the time of arrival at the two ears of (a) the oncoming wave front, (b) the transients in the sound pattern, and (c) difference phases of the tonal stimulus" (page 305).

Returning now to Coleman's scheme for establishing cue validity, it was a study by Halverson (1927) which quantified the influence of phase changes on pure tone lateralization. He attempted to find the greatest amount of lateral displacement from the median plane which could be obtained by changing the phase relationship by 180° between two, same frequency, pure tones, one delivered to each ear. Using an apparatus much like the stethoscope arrangement described earlier and a pointer system by which the listener could indicate the angle of the perceived sound, Halverson found that for the frequency series .6, 1.0, 1.4, 1.8, 2.2, 3, 3.5 with the remaining values rising in 1 kHz intervals from 4 kHz to 13 kHz, the maximum displacement of the image from mid-line went from approximately 75° for .6 kHz to 5° for 13 kHz, a negatively accelerated decay function. He concluded that for tones below 3 kHz median plane localization would present no difficulty, problems would be experienced for frequencies between 3 and 8 kHz, and median plane localization would be impossible for tones over 8 kHz.

This experiment showed that for low frequencies, phase could have considerable influence on the azimuthal position of the listener's image. A report by Steinberg and Snow (1934) quantified a second characteristic of low tones: they show relatively little intensity drop across the two ears. They based their calculations on data reported by Sivian and White (1933) who had determined the minimum audible field (i.e., the sound pressure level of a listener's threshold of audibility for a pure tone measured in a free sound field) for several pure tones ranging from .1 to 15 kHz. Steinberg and Snow re-analyzed this data to determine the intensity difference between the near and far ear for tones presented at 90° azimuth. The curve they obtained was generally a positively accelerated decay function, beginning with a zero dB difference between the ears for a .25 kHz tone, falling to 25 dB at 6 kHz, rising to 22 dB at 7.5 kHz, then falling again to 30 dB at 10 kHz.

Stevens and Newman (1936) used both of these reports to explain the results of their classic study on the duplexity theory. To avoid the problem of sound reflections and diffractions which had confounded the results of some previous research, they conducted the experiment out-of-doors on the top of a building. The blindfolded listener, sitting on a stool elevated 3.6 m above the roof, was presented pure tone and noise stimuli from a speaker which, by means of a boom arrangement, could be positioned anywhere around his interaural axis. Limiting the speaker positions to the right side of the subject and using 15^{o} separations from 0^{o} to 180^{o} azimuth, they found that the average error of localization rose from approximately 11^{o} at .60 Hz, to 20^{o} at 3 kHz, then declined to 13^{o} at 10 kHz. This compared with average errors of 8^{o} for a click stimuli and 5.6^{o} for a hiss. Referring to Halverson (1927) and Steinberg and Snow (1934), Stevens and Newman suggested that for low frequencies, i.e., below 1 kHz, the phase effect is large enough to account for the low error scores; while at higher values, i.e., around 5 kHz and above, interaural intensity difference can account for the improved performance. But in the region around 3 kHz neither of these cue mechanisms is particularly useful, explaining the high error scores. The contrast in performance between pure tone and noise localization was accounted for as follows:

> Noises in general have both high and low frequencies present. The low frequencies provide sufficient phase-differences and the high frequencies sufficient intensive differences for localization. The two types of cue render each other mutual

support, and the result is an accuracy of localization greater than that obtainable with pure tones. (page 305).

Mills (1958, 1960) was the next researcher to utilize data from physical acoustics and psychophysics to support the duplexity theory. In the 1958 study he determined, using the method of constant stimuli, the minimum audible angle (i.e., MAA--the difference limen for the azimuth of a source) for each of thirteen frequencies, ranging from 250 Hz to 10 kHz. MAA's were obtained for six azimuthal positions--0 , 30 , 45 , 60 , 75 , and 90°--in the horizontal plane, re interaural axis. Knowing the MAA for the various frequencies, he was able to make physical measurements of the phase differences occurring at the listener's ears when the stimulus was located one just noticeable difference (jnd) from the median plane. When Mills compared these values with the results of Zwislocki and Feldman (1956) who had determined, using a lateralization paradigm, the jnd in dichotic phase as a function of frequency, he found surprisingly good agreement up to approximately 1.3 kHz between the two curves. That is, the amount of phase difference required by the listener to notice a change in a tone's location was nearly identical to the phase difference present at the MAA for that tone. Around 1.3 kHz the jnd for dichotic phase becomes so great that it cannot be measured (Zwislocki & Feldman, 1956) and the two functions separate, suggesting that phase could not be instrumental for localization. Below that frequency, however, Mills argued that the correspondence between the physical and psychophysical curves strongly suggests that phase is the cue being used.

With the 1960 study, Mills attempted to establish similar functions for interaural intensity difference. He determined the jnd in dichotic intensity using a lateralization paradigm and the method of constant stimuli. By combining the median plane difference limens for each frequency from the 1958 study with a similar function by Sandel, Teas, Feddersen, and Jeffress (1955), he obtained a combined function which he then used to determine the actual intensity available when the tone stimulus was moved one jnd from the median plane. This was accomplished by taking the products of the combined function and a second, based on data of Sivian and White (1933), showing the interaural difference in intensity caused by moving various pure tone stimuli one degree from the median plane. Comparing the psychophysical function he had generated using the lateralization paradigm with the physical acoustic curve, Mills found that the two functions almost became one in the region between 1.5 kHz and 6 kHz. Below 1.5 kHz the two curves diverged, with the dichotic intensity required by the listener being considerably larger than what was physically available. Above 6 kHz the curves again separated, but here the listener still had useable intensity differences, suggesting that another localization mechanism must come into play at this point (Mills, 1972). With the close agreement between the physical and psychophysical in two studies, Mills felt the duplexity theory had been confirmed.

Kuhn's (1977) physical acoustics study of a manikin also supported the duplexity theory. His results showed that (1) interaural time difference (ITD) is independent of frequency below about .5 kHz, (2) ITD is also frequency independent above approximately 3 kHz, and

(3) minimum ITD occurs between 1.4 and 1.6 kHz for angles of incidence less than or equal to 60°. Kuhn's conclusion paralleled that of other supporters of the duplexity theory:

> Because of the asymptotic behavior of the ITD at low frequencies, the localization cue there remains relatively constant. Since the ITD decreases to a minimum between 1.4 and 1.6 kHz, the localization cue there is poor. Furthermore, the ILD [interaural sound pressure level difference] does not improve much until 2 or 3 kHz (depending on azimuth) is reached. The lack of either a strong ITD or ILD cue from 1.4 kHz to approximately 3 kHz, makes the localization poor .... The improvement in localization, as often shown in past subjective results, above 3 kHz results from the improvement in the ILD. (page 166).

Finally, it should be noted that the duplexity theory is relevant to other mammalia beside man. Using positive reinforcement operant conditioning procedures, Brown, Beecher, Moody and Stebbins (1978) tested three Old World monkeys (Macaca) on their ability to detect a change in the position of a pure tone stimulus. They trained the animals to press a response key (observing response) which initiated a series of pure tones from a reference speaker at 0° azimuth. On a given trial, the tone was shifted from the reference speaker to one of several comparison speakers located to the right of the animal, with the monkey indicating it perceived the change in sound locus by releasing the response key. For frequencies below .5 kHz, the animals had difficulty detecting a small change in azimuth (i.e., 2° to 10°), they improved considerably for tones between .5 kHz and 1 kHz, had difficulty with frequencies between 2 kHz and 4 kHz, and then continued to improve up to 8 kHz. Brown et al. calculated that the transition from phase to intensity mechanisms occurred in the interval between 1.25 kHz and 2.40 kHz, concluding on the basis of various transformations of the data that macaque directional hearing is consistent with the duplexity theory.

A fourth cue. Because spectral cues can occur both intra-aurally (i.e., at one ear) and interaurally (between ears), a short discussion will follow to outline the physical acoustics involved in the interaural case.

There are two main factors which create dichotic conditions, binaural distance difference and sound shadow (Gulick, 1971). Binaural distance difference, that is, the difference in path lengths to the two ears due to a sound being located off to one side of the median plane, gives rise to three interaural differences: intensity, time, and phase. The difference in intensity is not due to the diffracting or reflecting qualities of the head, but simply to the inverse first power loss (Coleman, 1963). That rule states that for each doubling of the distance of the source to the receiver, the sound pressure of the stimulus drops 6 dB (Cunniff, 1977). However, this decrease is not considered to be of any practical value to the listener for localization (Woodworth & Schlosberg, 1954; Yost & Nielsen, 1977) and need not be a consideration with respect to sound spectrum differences. Interaural time and phase differences are germane to the spectral cue in that the spectrum generated at the near ear will be neurally available before that of the far ear. Feddersen, Sandel, Teas, and Jeffress (1957) showed that a stimulus located directly opposite one ear requires approximately 670 μsec to reach the second ear. And for every centimeter a stimulus is located off to one side of the median plane, the sound requires an additional 29 μsec to reach the further ear (Thurlow, 1971).

Sound shadow, the second factor, is caused by obstructions such as the head, pinnae, or torso reflecting or diffracting sound waves. Frequencies above approximately 1 kHz show little diffraction (i.e., a tendency to bend around the head) but instead are reflected, causing a drop in sound pressure at the far ear (Feddersen et al, 1957). Below 1 kHz diffraction occurs and the sound pressure level across the ears remains relatively constant. Because the head has this low pass filter effect (Mills, 1972), it can modify the spectral characteristics of a complex stimulus. The pinnae (Batteau, 1968; Blauert 1969/1970) and torso (Gardner, 1973b) have also been shown to have a filter type effect on complex stimuli.

It is apparent from this discussion that interaural spectral cues (knowable psychologically, through introspection, as tone color or timbre differences) will only be generated when the stimulus is complex enough to be differentially affected by the interfering object. When that is the case, there must be some systematic change in the sound spectrum available at the two ears if the cue is to indicate changing sound loci. The belief that the head and pinnae create spectral modifications is an old one, but objective evidence suggesting the changes occur systematically consequent upon changes in stimulus position has only been shown recently (Batteau, 1968; Blauert, 1969/70).

Angell and Fite (1901), studying the localization abilities of normal and monaural subjects made a clear statement concerning spectral modifications:

> Sounds which are complex in nature undoubtedly undergo modification through the damping and reinforcing of their partial tones by the pinnae, the external meatus and the head, in a manner which must vary somewhat regularly with variations in the spatial position of the object from which the sound emanates. When the changes in these objective positions are small, the corresponding changes in the quality of the sounds are ordinarily minute. (page 244).

Ferree and Collins (1911) reported that timbre differences are an important component of Rayleigh's (1877) binaural ratio. Using a sound-cage (a half-sphere, formed from metal rods, under which the subject sits, the bars being used to mount the sound sources), they reported that listeners had more difficulty localizing the position of a 480 Hz tone than of a Galton whistle, the latter being the source of the complex noise. They concluded from this and additional work that the binaural ratio was composed of two components: interaural intensity and timbre differences.

Trimble (1928), discussed earlier, referred to Ferree and Collins' (1911) data when he suggested that a 'mass difference effect' could also contribute to the sound pattern that results in directional hearing. Interestingly, he suggested that one way to examine this cue would be to increase the complexity of the stimulus at one ear while holding it constant at the second, a technique not unlike that used in some recent work (e.g., Searle, Braida, Cuddy, & Davis, 1975).

Stevens and Newman (1936) reported that spectral cues had proved useful when listeners localized click or hiss stimuli. The click was produced by applying a voltage to a speaker for an instant; the hiss, by blowing air through a small brass tube whose end had been cut and pinched. Although at the time of testing, a listener could not express what it was about the hiss which helped him to localize, studies after the test series showed that the hiss sounded differently at certain locations: When in front, it was more "shh" and less "sss", and it appeared louder than when coming from behind. Stevens and Newman concluded that the head differentially affected the frequencies of the hiss, resulting in qualitative changes in its spectrum; they did not comment on the click stimulus.

In these early studies the presence of a spectral cue was typically determined using introspection; for example, the subject would report changes in tone color. But there was no objective record of what had occurred at the listener's ear. With the coming of more sophisticated electronic devices in the 1940's, researchers could place small microphones in the meatus and record sound pressure changes near the eardrum. This was the advance which eventually allowed the comparison of psychophysical data with physical.

Stevens and Newman (1936) had argued that the head was responsible for spectral changes, but the early physical studies, using small condensor microphones, indicated that the pinnae too were having considerable influence on the sound field.

Wiener and Ross (1946) inserted a condensor microphone up to within 1 mm of a listener's eardrum and recorded the sound pressure changes which occurred when various pure tone stimuli, ranging from

.2 kHz to 8 kHz, were presented at that ear from each of three azimuths, 0°, 45°, 90°. The results were surprising. They found that nearly all frequencies were boosted somewhat in intensity over free-field values, the highest increase being 22 dB re 1 volt/dyne/cm^2 for 3 kHz. As the source position was moved from the median plane to 90°, the functions tended to increase although still remaining quite similar in shape to one another, suggesting that changes in sound locus might be causing systematic changes in the sound spectrum. When the meatus was blocked off and the microphone was placed at the plugged opening, increases in sound pressure over free-field values were still noted. This was an indication that the head and pinna were responsible for part of the total amplification effect. Finally, when the listener cupped his hand around the pinna with the microphone again located near the tympanic membrane, there were increases of from 5 to 18 dB over the usual function for the mid-line position. A pinnae effect was strongly suggested.

Jongkees and Veer (1958b) also studied the influence of the auricle on a sound field. Mounting a microphone at the eardrum position inside a manikin head having artificial pinnae, they measured the directional activity of the auricles on pure tones, ranging from .5 kHz to 10 kHz, as the head was rotated on its vertical axis through 360°. They reported that below 2 kHz the pinnae had little influence on the sound field, but their directional activity increased considerably between 5 kHz and 10 kHz. When they compared these polar diagrams to similar functions generated using a head without pinnae, they found the latter diagrams had fewer details and showed areas of secondary maxima that Jongkees and Veer suggested made directional hearing difficult.

Fisher and Freedman (1968b) performed a study indicating that spectral changes caused by the head are not sufficient for localization: pinnae must be present. The subjects were required to report while blindfolded the location of a pulsed, white noise stimulus which was randomly presented from each of eight equally-spaced positions around their interaural axes. They were tested under two head position modes, head free (20 subjects) and fixed (7), with each mode having three listening conditions: (1) own pinnae, (2) no pinnae, the subjects' auricles being covered by sound-attenuating muffs having holes through their centers from which protruded 10 cm long metal pipes, and (3) artificial pinnae, these being connected to the listener's meatus by the same pipes as in Condition 2. Fisher and Freedman reported that there were no differences in performance among the three conditions for the head free mode, but for the head fixed mode, the own pinnae and artificial pinnae conditions differed significantly from the no pinnae condition but not from each other. They concluded that in the absence of head movement having pinnae, even an artificial pair, was the important requirement for directional hearing.

A physical acoustics study by Shaw and Teranishi (1968) was the first clear indication of how the pinnae, without the confounding of head shadows, created spectral changes in the wave front. Shaw and Teranishi constructed a life-size, rubber replica of the external hearing apparatus, i.e., pinna, concha, and meatus, and mounted the arrangement on a rigid plane. By placing a condensor microphone at several positions within the meatus and then presenting pure tone stimuli, ranging from 1 kHz to 15 kHz, from various azimuths and elevations, they were able to show the strong directional characteristics of the pinna. For example, with the meatus blocked and the microphone placed over the top of the plug, systematic changes in sound pressure as a function of frequency were recorded as the stimulus source was rotated through 180° re the interaural axis. Especially noticeable was a deep dip in the 0° function at approximately 9.5 kHz, a feature which has since been confirmed (e.g., Bloom, 1977).

In a series of experiments starting in the early 1960's and concluding with a summary statement in 1968, Batteau also examined pinna transformation, but less formally. Working with large, model replicas of the pinna, he found that the pinna's convolutions cause reflections of the in-coming sound such that the delay between the direct and reflected waves varies systematically with azimuth and elevation of the source. As the noise stimulus, a sharp click, was advanced from 130° to 0° in the horizontal plane, the delay increased monotonically from approximately 10 μsec to 80 μsec. Similar effects were obtained when the click was moved from above, to the side, and then below the pinna, the delay increasing from 100 μsec to 300 μsec. Batteau (1968) argued that these delays were processed by the neural system, with the various temporal patterns produced corresponding to unique loci in auditory space. This interpretation has been challenged, however, and it appears more likely that the reflections off the pinna cause spectral changes which are then processed by the auditory system (Wright, Hebrank & Wilson, 1974). In the median plane, these spectra will be similar at each pinna but not identical (Searle, Braida, Cuddy & Davis, 1975), and as the source is moved to one side, the two transformations will become increasingly different (Batteau, 1967). Batteau believed that the second transform provided redundant information which improved acuity. But he also argued, as did Fisher and Freedman (1968a), that one pinna was sufficient for reasonably accurate localization, a view to be discussed later.

A number of studies have provided both formal and informal evidence that the listener does make use of spectral changes produced by the auricles--e.g., Blauert (1969/70), Hebrank and Wright (1974b), Searle et al. (1975), Bloom (1977). All of these studies were conducted in the median plane, for it is here that interaural time and intensity differences are believed to be absent, although interaural spectral cues are not (Searle et al., 1975). At this position, then, spectral cues may be unambiguously assessed.

On the basis of his work, Blauert (1969/70) has advanced the hypothesis that the pinna behaves like a comb filter: It enhances some parts of the frequency spectrum while depressing others. When there is sufficient energy in certain of these "preference bands", the listener receives a directional sensation, regardless of where the source is actually located. This effect was nicely illustrated using noise signals of one third octave band width, with center frequencies from 125 Hz to 16 kHz. The subjects, tested in a darkened, anechoic chamber, were required to indicate from which sector of the median plane they perceived the sound. The "front" sector extended from -15° to $+45^{\circ}$, "overhead" from $+45^{\circ}$ to 135°, and "back" 135° to -15°. Twenty-two different bands of noise were randomly presented once from two speakers located 3.30 m from the interaural axis, one at 0° the other at 180° re median plane. Blauert found that center frequencies between 250 Hz to 500 Hz and 2.5 kHz to 5 kHz gave the impression of a "front" sensation, between 5 kHz to 8 kHz an "overhead" sensation, and between 630 Hz to 1.6 kHz and 10 kHz to 12.5 kHz a "back" sensation. This is strong evidence for the pinna effect when it is noted that all twenty-two bands were presented from only two positions.

Hebrank and Wright (1974b) reported a similar effect using a different testing paradigm. The subject's task was to locate the position of a stimulus which was randomly presented via a moveable speaker from any one of nine positions, spaced 30° apart and ranging from -30° to $+210^{\circ}$, in the vertical plane. The subjects were divided into three groups, each group receiving a different set of stimuli. Group one localized 3 types of white noise: (1) filtered to have one of six high-pass cutoffs from 3.8 kHz to 15.3 kHz (2) filtered having one of seven low-pass cutoffs from 3.9 to 16.0 kHz and (3) unfiltered; group two localized filtered white noise having one of 12, 1/12 - octave bandpass peaks, ranging from 4.0 kHz to 14.5 kHz; and group three localized bandstop notches at 12 frequencies from 6.2 kHz to 17.8 kHz. Hebrank and Wright reported that some of the filtered sounds clearly bring about a sensation of direction and summarized the results in this way:

> Frontal sounds are cued by the low-pass cutoff between 4 and 8 kHz of a notch and increased energy above 13 kHz. Overhead sounds are cued by a peak near 8 - 9 kHz and its accompanying 10 kHz low-pass slope. Posterior sounds appear to be cued by a 10 kHz high-pass slope leading to a peak near 12 kHz. (page 1832).

A recent controversial report by Searle et al. (1975) has given clear indication that in the median plane slight differences between pinnae transforms can be perceived. This is a different argument from the typical one stating that in this plane the two transforms simply complement one another. The Searle et al. position, then, makes pinnae transformations a much more interaural cue than the redundant coding hypothesis of Batteau (1968). The distinction is of theoretical importance, especially with respect to localization models (Searle et al., 1976).

As mentioned earlier, Searle et al. (1975) used Coleman's (1963) scheme in their attempt to document the utility of interaural pinna spectrum differences. Accordingly, the study was divided into three parts. In the first, a condensor microphone was inserted into each ear canal of the listener and, using a boom and speaker arrangement, the output of the microphones was recorded as the speaker was moved in 15^{o} steps from 0^{o} to 180^{o} in the vertical median plane. Upon comparing the two functions from each ear, Searle et al. found the expected angle-dependent transformations reported by Batteau (1968), but in addition they noted considerable differences between the functions at each presentation angle.

In the second part of the study, Searle et al. showed that the notches created in the sound field by the pinna transform could be detected by the listener, although they did not show that the differences between the two spectra (i.e., one from each ear) were detectable. Both formal and informal procedures were used to determine notch acuity. In the former case, Searle et al. compared their physical acoustic functions with the psychophysical curves of Wright, Hebrank, and Wilson (1974) who had determined the Reiz Limen (RL) and Differenz Limen (DL) for delay time detection of pinna reflected sound. The comparison showed that the notches in the pinna transforms were well above the listeners' thresholds, suggesting that these dips should be detectable by the nervous system. The informal procedure consisted of having the subject position a pure tone at that place in the median plane where it sounded most faint. Invariably, this location matched the position on the pinna transform function where a dip occurred at that frequency and elevation.

In the final section of the study, Searle et al. again drew upon formal and informal data to support their position. Other researchers, for example, Butler (1969b) and Gardner (1973b), had shown that when one ear was plugged, vertical plane localization became poorer. This suggested to Searle et al. that the decrement was due to the loss of the interaural pinna disparity cue. More formally, they conducted an experiment where sounds, delivered from several elevations in the vertical plane and recorded by condensor microphones located in both ear canals, were played back to the listener via headphones in the normal fashion, i.e., left channel to left ear, right channel to right ear, or by delivering the left channel or right channel to both ears. Under these conditions of test it was found that listeners could detect the elevation of the sound most accurately when the channels were presented in the normal fashion, suggesting that each ear had generated a "different view" during recording. Hebrank (1976) has criticized the study, but the data do appear highly convincing. And if binaural pinna disparity is a reality in the median plane, then the role of spectral cues at other locations off mid-line must be entertained (Searle et al., 1976).

Based on this review, the following conclusions appear justified with respect to an interaural spectral difference cue: (1) the existence of such a cue seems well substantiated, (2) the pinnae are implicated as one cause of the difference spectra, and (3) the cue seems appropriate only for a complex sound field. There may be some objection to the last point, for Batteau (1967b) has stated that only two pure tones would be necessary for accurate localization using the pinna transform. However, in the natural environment, the presence of a stimulus containing only a few discrete frequencies would be typically quite remote, suggesting that the cue has not "evolved" for pure tone localization. It may be hypothesized, then, that there are two binaural cue systems, one for use in artificially contrived situations (i.e., pure tone localization), utilizing intensity, phase, and time differences <u>separately</u>; the other for use in more complex sound fields (i.e., those found in the natural hearing environment), utilizing spectra differences which have time, phase, and intensity components.

How does the nervous system "know" that a specific, spectral change denotes a unique locus in auditory space? Bloom (1977) suggests that: "... the auditory system in cooperation with the brain has 'learned' that specific spectral modifications are carriers of directional information" (page 827). And with respect to the complete binaural cue system, a more general answer by Plenge (1974):

> The first condition for localization is the ability learned in early childhood, to classify perception events

as sound events. This ability may comprise, besides the perception of direction and distance, the ontogenetic earlier fusion of the information coming through both ears into one general acoustic image. The data stored during this learning process are recalled automatically whenever any sound event (sound stimulus) brings about a hearing event. This long-term storage can be cleared only gradually, and slowly filled again. (page 950).

Influencing Factors

In the introduction it was mentioned that many factors can influence the accuracy of localization. Six such factors will be considered here: (1) head movement, (2) pinnae occlusion, (3) stimulus complexity, (4) subject training, (5) azimuth of sound source, (6) elevation of sound source.

Head movement. Young (1931) was one of the early researchers to examine the role of head movements in auditory localization. He used a stethoscope arrangement, much like the one mentioned earlier, to dissociate the listener's ears from his head, thus eliminating the effects of head movements on perceived location. Typically the listener sat in a partially sound-proof room, the pipes in his ears extending through the wall into an adjoining room where their ends terminated onto trumpet-shaped horns. The horns were mounted horizontally, 17.3 cm apart, with their open ends facing away from each other much like actual pinnae. A disc marked off into 12 equal divisions was situated with its center directly below the middle of the trumpetal axis, allowing accurate placement of the stimulus source, a telephone receiver generating a double click. The listener's task was to detect the locus of the click when it was presented randomly from one of the 12 positions. Using this apparatus, Young conducted a series of experiments from which he drew the following conclusions:

> (1) The distinctions of up, down, front, back and intermediate directions are objectively impossible when head movements are ineffective. (2) Subjects can distinguish right from left and intermediate right-left directions with objective accuracy. (3) The course of the phantom [the sound image] is restricted to an arc outside of the visual field which for normal subjects is generally in the rear of the head at or above the level of the ears. The vertical angle of this arc varies from subject to subject and has no discovered relation to the binaural stimulus pattern. (page 117)

Young's conclusions must be examined with caution, however. Eliminating the auricles has, as was shown in the previous section, a significant influence on localization.

Wallach (1939) outlined a theory of localization in which head movements were an important factor. He suggested that the so-called primary cues, interaural time and intensity differences, simply served to localize the sound to the surface of a cone shaped area (the cone of confusion) on either the left or right of the listener, the cone having its apex at the center of the interaural axis, and its base parallel to the median plane. Without head movement, all the listener would know was that the stimulus appeared to be at one ear with an angle of incidence (lateral angle) determined by the slope of the cone. Wallach argued that to resolve this cone of confusion a head rotation toward the stimulus was necessary. Such a movement would change the lateral angle and thus the influence of the primary cues, allowing the sound to be isolated to either the front or back. And because the head cannot rotate without cutting through the equatorial plane, the elevation would also be determined. Wallach's theory suggests that without head movement all the listener can know for sure about the locus of a sound is whether it is to the left or right of the median plane, a one dimensional sensation.

Klensch (1948a, 1948b) attempted to test this theory using the familiar stethoscope arrangement, the ear pipes, as in the Young (1931) study, being connected to funnels which served as pinnae. With the funnels facing directly in front and fixed in position, such that movements of the head did not change the distance of the funnels from the sound source at 0°, the listener upon moving his or her head could only perceive the click stimulus as being at the center of his or her head. If one funnel was moved forward and the other backward or vice-versa with the head motionless, the image moved from left to right inside the head. When the funnels were moved during head rotation as actual pinnae would move, the sound was perceived in its proper location in front. But if the funnels were crossed in this same condition, the sound appeared in back. In those instances when the sound was correctly perceived, the head movements were approximately 10° and the funnels were moved about 3 cm. This work appeared to support Wallach's theory, but again the pinnae had been eliminated from the sound field.

Koenig (1950) conducted a similar experiment but replaced the funnels with a life-sized, artificial head having receivers at the ear positions which fed to a pair of earphones for the listener. With the two receivers removed from the manikin and placed varying distances apart, the listener could not accurately locate the position of a talker walking around the test room. Although the sound image of the talker's location did change position, it was always confined to a semicircle behind the listener. When the receivers were placed back in the manikin and it was motorized so as to mimic the head movements of the listener, the listener had no difficulty in making the manikin face the talker, the talker's image appearing directly in front of the listener. Although, Koenig did not make it clear whether the manikin had pinnae, the value of head movements in localization appears convincing here.

Jongkees and Veer (1958b) presented evidence suggesting that small head movements are not required. They tested the ability of two groups of subjects, one allowed free head movement, the other required to keep their heads facing forward, to localize the position of a click stimulus presented randomly from one of eight speakers located at 15° intervals, beginning at 315° and going clock-wise. The subjects in both conditions performed equally well on the task. This result, however, must be interpreted with caution as Jongkees and Veer make no mention of having instructed the head free subjects to move their heads. There is a distinct possibility that few actually did so.

Burger (1958) has shown that when the head is not rigidly fixed, front-back discrimination is most accurate. The testing apparatus consisted of four speakers, two located 5.5 m in front, two the same distance behind. They were offset 1.5 m to the right of the median plane, with one of each pair being a dummy. There were four within-subject conditions: (1) the listener's head was clamped in place and both pinnae were unobstructed, (2) the listener's head was clamped as before, but the left ear was masked using a headphone delivering white noise, (3) the listener's head was free, but both ears were covered with earphones to eliminate the effects of the pinnae, and (4) both head and pinnae were unobstructed, and the listener was asked to avoid excessive head movements. Test signals were 12, 1/1 octave bands of filtered white noise from 150 Hz to 12.8 kHz presented at three different levels (30, 50, and 60 dB) in a semi-random fashion. The listener's task was to indicate from which direction a pulse of noise came, front or back. The order of the listening conditions with respect to overall percentage correct localizations was as follows, going from highest to lowest: (1) head free, both ears free, (2) head clamped, both ears free, (3) head free, both ears covered, and (4) head clamped, one ear covered and masked. Burger concluded that both head movements and the presence of the pinnae contribute to the ability of a listener to perform front-back discriminations, although he did not feel these two factors completely explained the phenomenon.

Fisher and Freedman (1968b), whose study was reviewed earlier (page 27), also found front-back confusion was reduced when head movements were allowed. When subjects tested in the head free mode, own pinnae condition were compared with their counterparts in the head fixed mode, the number of front-back confusions was found to have increased from one per 112 localizations for the former to 13 per 320 for the latter, approximately a fourfold increase.

In contrast to this study Batteau (1968) reported no front-back confusions when head movements were restricted. His testing paradigm was very different, however. The listener performed the localization task using headphones while seated in a room adjoining the test chamber. In the chamber, silicone rubber molds of the listener's ears, having high-fidelity microphones mounted at the meatal openings, were joined by a narrow bar which oriented and spaced the pinnae exactly as they would be on a listener's head. This pinnae arrangement was mounted on a stand in the center of a circle, marked off into 16 equally spaced segments. The subject was required to locate the position of a maraca when it was shaken at each of the 16 positions. Head movements were, of course, of no value to the listener in this situation. Nevertheless, there was not one instance of front-back confusion.

To date, the most comprehensive study of head movements has been conducted by Thurlow and Runge (1967). To ensure the movements were all uniform, the subject wore a mechanized head frame which moved his or her head the required direction and distance on each trial. There were four motion conditions: (1) No motion. The subject's head was held stationary during stimulus presentation. (2) Rotate motion. The subject's head was rotated (i.e., turned about its vertical axis) 45^{o} to the left, then, 0.5 sec after stimulus onset, it was rotated to the right, back to 0^{o}. (3) Pivot motion. The subject's head was pivoted (i.e., tilted toward one shoulder) 15^{o} to the left, starting 0.5 sec after stimulus onset. (4) Rotate-pivot motion. The subject's head was rotated 45^{o} to the left, then, 0.5 sec after stimulus onset, it was rotated 45^{o} back to straight ahead, and then pivoted 15^{o} to the left. The stimuli were high and low frequency clicks and high and low frequency bands of thermal noise of 5 sec duration. They were presented from 14 loudspeakers mounted at various positions on the front and side walls of an anechoic room. The blindfolded subject, sitting in the middle of the room and facing the front wall, indicated his or her localization choice after stimulus offset by pointing with a meter stick. Independent groups of 10 subjects were tested on both click and thermal noise stimuli under one of the four motion conditions. The results showed that with respect to front-back reversals, subjects using rotate or rotate-pivot movements displayed little confusion with sounds located directly ahead, displacing them to the rear only occasionally. Subjects in the no motion and pivot conditions were less successful, with up to 90 percent confusing front and back when the stimuli were presented at 0°. The central findings reported generally involve statistical comparisons between the no motion and rotate conditions, the main concern of the study. The rotate condition differed significantly from the no motion condition on horizontal error both for high and low band <u>noise</u> stimuli but only for low band on vertical error, the rotate condition having fewer errors in all these comparisons. For low band noise, both pivot and rotate-pivot conditions had fewer errors than no motion on vertical localization. The rotate condition had significantly less horizontal error than the no motion condition on both high and low band <u>click</u> stimuli, but head rotation did not significantly reduce vertical error for either high or low band stimuli versus no motion. There were no differences between the no motion and pivot or rotate-pivot conditions on vertical localization for either low or high band clicks. Thurlow and Runge also conducted a short experiment using the same test paradigm but allowed the subjects to move their heads, but not their bodies, in any way they chose. The results were not statistically different for low or high band noise from those of the induced rotate condition. They concluded from the series that induced head rotation reduced horizontal localization error, and that rotation, pivot, and rotate-pivot movement decreased vertical error for low frequency noise stimuli.

In summary, these studies create the general impression that head movements under binaural conditions do reduce front-back confusions, and can improve horizontal and, in some cases, vertical localization.

Pinnae occlusion. Jongkees and Veer (1958b) reviewed some of the early literature and found that several studies, e.g., Burnett (1895), Munsterberg (1889), Van Gilse and Roelofs (1930), and Jongkees and Groen (1946), had shown that such manipulations as filling-in the convolutions of the pinnae or flattening them against the head made directional hearing less subtle.

More recent work by Roffler and Butler (1968a) has confirmed these early findings. In one experiment reported in that paper, the influence of the pinnae on vertical localization was examined. Eight subjects were required to localize the position of a stimulus sounded from behind a vertical, white, cloth panel. The panel was divided by black strips into 13, 10.2 cm high sections, numbered "1" to "13", starting from the floor. Four matched speakers were located behind it at -13, -2, 9, and 20° re the median plane, zero degrees on the panel (i.e., between numbers 6 and 7) being at the same height as the subject's interaural axis. During testing the subjects sat facing the panel at a distance of 4.6 m. Their chair was equipped with a headrest to control for head movements. There were two test series. During the first, the subject localized both broad-band noise and 8 kHz high-pass filtered noise. The second series was identical except the subject's ears were covered with a Plexiglas headband which flattened the pinnae against the head. Sound was allowed to enter the meati via two small adjustable apertures. The test results showed that listeners wearing the headband had difficulty locating both types of noise stimuli. Average error rose monotonically from-4° at speaker position -13° to approximately -24° at position 20°, while without the band, average error never went above-6° at any speaker location and was usually below-4°. Roffler and Butler also reported that four listeners wearing this same headband during a horizontal plane localization task did not show impaired performance over their normal ability. Unfortunately no further details were given.

The most systematic study of pinna occlusion effects which has been reported was conducted by Gardner and Gardner (1973a). Their apparatus, located in an anechoic chamber, consisted of nine loud-speakers arranged in a vertical (median plane) arc 3.1 m from the listener's chair, the speakers being 4.5° apart, center to center. The stimuli used were bands of random noise, ranging from full band-width to narrow bands centered at 2, 3, 4, 6, 8 and 10 kHz. There were four pinna conditions for each subject: (1) all cavities open, (2) scapha only filled (S condition), (3) scapha and fossa filled (SF condition), and (4) scapha, fossa, and concha filled (SFC condition), with an appropriate size opening being made to the meatus. A mold-making rubber was used to construct the pinnae plugs. Testing took place in two series, one with the subject facing the speaker arc, the other with his or her back to it. After each presentation from a randomly chosen speaker, the subject was required to express his or her localization choice verbally. The results were reported in terms of an error index, "0" representing no errors, "100", guessing. For the anterior series, the results were as follows: With wide band noise, the error index rose from approximately 10 for all cavities open to 20, 43, and 70 for the S, SF, and SFC conditions, respectively. The narrow bands all had higher error scores than the wide band. For example, the index for the band centered at 2 kHz went from 70 for all cavities open to 73, 80, and 100 for S, SF, and SFC, respectively. This band produced the most extreme values of all those examined. In the posterior series, i.e., the speaker array at the listener's back, the error scores were higher overall than for the first series, partly owing to the lack of visual cues. In the wide band case, for example, the index went from 40 with all cavities open to 40, 54, and 100 for S, SF, and SFC respectively. For the 2 kHz band, all pinnae conditions had error indexes above 83. Again, this narrow band stimulus produced the most extreme error values. From these results, Gardner and Gardner drew the following conclusions regarding median plane, localization: (1) accuracy decreases with increasing pinnae occlusion, (2) accuracy is better in the anterior than posterior region, (3) as the frequency position of the band increases, so does localization ability, (4) performance is better for broad band stimuli than narrow band for all states of occlusion, and (5) without occlusion, i.e., all cavities open, wide band results are similar to those of 8 and 10 kHz centered bands.

Although there are few studies directly concerned with pinnae occlusion, the two reviewed in this section strongly suggest that vertical plane localization accuracy is decreased by pinna modification.

A similar conclusion may eventually be drawn for the horizontal plane case, but up to the present time there has been no systematic study similar to Gardner and Gardner (1973a) on which to base such a conclusion.

Stimulus complexity. Throughout the review it has been apparent that complex stimuli, whether white noise, clicks, or hisses, were more often localized in the correct location than were pure tones (recall, for example, Ferree & Collins, 1911; Sevens & Newman, 1936). In this section, studies which have sampled various parts of the continuum of stimulus complexity, ranging from discreet pure tones through speech to white noise, will be reviewed.

Mills (1958) was the first to quantify the influence of frequency on directional hearing acuity. As was indicated earlier (page 19), he determined the MAA's for 13 pure tones, ranging from 250 Hz to 10 kHz. For MAA's calculated at 0^{o} azimuth, he found that from .25 kHz to .8 kHz, the Differenz Limen remained relatively constant at approximately 1^{o}, rose rapidly at 1 kHz to a peak of 3.5^{o} at 1.5 kHz, dropped to 1.5^{o} at 3 kHz, where it remained until rising again at 6 kHz to a second peak of 3.5^{o} at 8 kHz, dropping again to 2.5^{o} at 10 kHz.

Harris and Sergeant (1971) calculated a similar function using moving stimuli, both pure tone and white noise. In this study, the blindfolded subjects, three experienced listeners, determined whether a loudspeaker, mounted on a moveable stage located 3.04 m from them, was moving either left or right during the stimulus presentation. The method of constant stimuli was used to determine MAA, with each series of runs consisting of 5 trials to the right and 5 to the left given in random order. MAA's were calculated at 0^{o} azimuth for four pure tones, 0.8, 1.6, 3.2 and 6.4 kHz, and white noise. The results showed that the Differenz Limen for all five stimuli was about 2^{o}. The data from this and the previous study suggest that under certain conditions of test, surprisingly small changes in the location of some pure tone stimuli can be perceived; and, in addition, this acuity can equal that for white noise.

Gardner (1968) has determined the accuracy of angular localization of speech when it is presented from directly in front of the listener. Twenty subjects were used, 15 of whom were experienced listeners, the remainder being naive to auditory research. Testing took place in an anechoic chamber, with the listener seated 6.7 m from a horizontal arc of seven loudspeakers, numbers "1" and "7" of which were dummies. The speakers were separated from each other by 2.5^{o} of arc, the fourth speaker located at 0^{o} re the listener's median plane. The test stimulus consisted of a five-voice, high-quality, speech sample (i.e., five individuals reading consecutive parts of a passage), the listener's task being to locate the speaker from which the sample came based on 7 to 12 sec. of presentation. During the presentations, the listeners were free to move their heads about the vertical axis. The results showed an overall localization error of 1.5^{o}, an amount comparable to that found in the above two studies for white noise and pure tone stimuli.

Normal, binaural localization in the median plane, as has been intimated, is strongly influenced by stimulus complexity. In a study by Roffler and Butler (1968a), discussed earlier (page 41), two other experiments were outlined examining the influence of stimulus bandwidth on vertical localization. In the first, which used, along with the second, the same test apparatus previously described, six listeners were tested on their ability to localize six stimuli: (1) broad-band noise, (2) low-pass filtered noise (less than 2 kHz), (3) high-pass filtered noise (two stimuli--greater than 2 kHz, and greater than 8 kHz), (4) .6 kHz tone burst, and (5) 4.8 kHz tone burst. Each stimulus was presented 80 times, the speakers activated in a quasi-random fashion. Roffler and Butler found that the listeners were unable to correctly localize the tone bursts or the 2 kHz low-pass noise. The remainder could be accurately placed.

To investigate the good performance found using stimuli with frequencies above 2 kHz, they conducted a second experiment similar to the first. Here, they were interested in what range of high frequencies was required for accurate localization. Thirteen low-pass filtered noises were used, differing only in their upper cut-off frequencies which ranged from .5 kHz to 12 kHz. Six listeners were tested using the same presentation format as used in the first experiment. The results showed that for noise bands below 7 kHz localization judgments were inaccurate, but above this value there was an abrupt improvement. From these two studies, Roffler and Butler concluded that to localize sounds in the median plane accurately, the listener must have a complex sound containing frequencies above 7 kHz.

Hebrank and Wright (1974b) have qualified this conclusion somewhat. They tested subjects on median plane localization over 240^{o} of arc versus 33^{o} for Roffler and Butler (1968a). In this experiment the directional accuracy of 10 subjects was examined using seven, low-pass cut-off frequencies and six high pass. The stimulus loudspeaker was located .9 m from the listener and could be rotated in an arc to nine positions, 30^{o} apart, ranging from −30 to 210^{o}, 0^{o} being at the level of the listener's interaural axis. Each stimulus was presented twice from each speaker position; standard randomization procedures were used. Hebrank and Wright found that localization performance was not affected when frequencies below 3.8 kHz and above 16 kHz were absent, implying that frequencies between 3.8 kHz and 16 kHz are germane for the task. They suggested that the results were not in conflict with those of Roffler and Butler (1968a); the difference simply indicating that different spectral features would be required as degrees of arc increased from front to back.

Returning again to Roffler and Butler, these researchers (1968b) explored an interesting phenomenon with respect to pure tone localization in the median plane: High tones regardless of their objective position in auditory space are perceived to originate above low tones. The testing apparatus used in this study was identical to that described previously in the 1968a paper, the stimuli being nine tone bursts with frequencies from .25 kHz to 7.2 kHz. Five subjects were tested, with all stimuli and speaker locations presented in a quasirandom order. It was found that for each of the four speaker locations, the tones were perceived almost without exception in ascending order of frequency, starting from panel five with .25 kHz and ending at panel 11.5 with 7.2 kHz. This surprising effect has also been reported by Pratt (1930) and Trimble (1934).

This section has shown that in the frontal area, a change of one or two degrees is sufficient for a listener to notice that either a pure tone, speech segment, or white noise has changed location. In addition, it seems that for a stimulus to be accurately localized in the vertical median plane it must be complex; pure tones are not localized objectively here.

Subject training. The influence of training on binaural localization in either the horizontal or vertical plane is not a factor which has been systematically varied in any of the localization studies the author has reviewed. Researchers do report giving their subjects training trials, but these are administered usually for purposes of experimental control (e.g., Fisher & Freedman, 1968a) or to familiarize the subject with the localization task (e.g., Gatehouse & Cox, 1972). There is a need, then, to determine the influence of this factor on normal directional hearing.

Azimuth of sound source. Munsterberg (1889) determined that directional hearing was most accurate in front of the listener, less so at the sides, and poorest at the back. He was not quite right, however.

Bloch (1893) in a classic study corrected the error. He calculated the angular differential threshold and found it was least in the front, increased for positions behind the listener, and was largest at the sides. He also noticed an interesting characteristic of directional hearing: a listener has no difficulty distinguishing a sound on the left side from one on the right, but acuity at the sides is poor; whereas, front and back positions are readily confused, yet small changes in sound location can be easily noticed here.

Stevens and Newman (1936), in the study described earlier (page 18) showed how their data confirmed Bloch's (1893) results. When they calculated the average error of localization for pure tone stimuli presented from 0, 15, 30, 45, 60, 75, and 90° azimuthal positions, they obtained respectively, the following averages: 4.6, 13.0, 15.6, 16.3, 16.2, 15.6, and 16.0°.

This trend was the same as that found by Mills (1958, discussed earlier, pages 19 & 44) in his calculations of MAA's, determined for various frequencies at five angles. He found, for example, that for a 1 kHz tone, the MAA went from about 1° to 1.5°, 3.5°, 8.5° and greater than 40°, as the reference position of the sound source was moved respectively from 0 to 30, 60, 75, and 90° azimuth.

Searle et al. (1976) have also examined the influence of azimuth of a sound source on localization ability. They showed that as the total angle spanned by the loudspeakers (i.e., the angle from the center of the first speaker to that of the last) used for testing is increased, the error standard deviation (representing listener acuity) rises as well, indicating decreasing localization ability. For example, when they plotted standard deviation of localization in degrees as a function of total angle spanned by the speakers in degrees, it was found that the curve rose from 1° at 1° speaker separation to 10.3° at 48° separation.

Shelton and Searle (1978) have shown that this increase in error standard deviation is not simply a result of the wider spans entering regions where localization ability is known to decrease--i.e., at the sides. They tested the ability of listeners to localize single, 200 msec bursts of white noise presented from eight loudspeakers arranged 11.2° apart on a 2.7 m diameter hoop. The listeners were seated at the center of the hoop, and the arc of speakers was positioned on the left, with the first speaker located at 0° and the last at 281.6° azimuth. Thirty subjects were tested, ten on all eight speakers (full-span condition), ten on the front four only (half-span condition), and ten on the back four only (half-span condition). The results based on 40 test trials per listener were tabulated in terms of average error score, the angular difference between the presented and reported speaker position on each trial, averaged across the 40 test trials. As well, the data for the full-span condition were analyzed as if the subjects had only localized the front four speakers and the back four, thus breaking the full-span into two, half-spans, i.e., full-span front and full-span back, which could then be compared to the actual half-span conditions. The average error scores in degrees for the four, speaker span conditions were as follows: half-span front, $.4^{\circ}$; half-span back, 2.2°; full-span front, 1.5°; full-span back, 4.6°. Shelton and Searle argued that these results show an effect due to decreasing listener acuity at the sides, i.e., performance was best in the front regardless of span, and also a context effect due to speaker span, i.e., errors were smaller in both the front and back for the half-span condition. They handled a possible criticism against this interpretation as follows:

> It is possible that the difference between the two conditions was due to a difference in the number of alternatives rather than the angular extent of the speaker array, since the two variables were confounded in the experiment. However, the general success found by Searle, Braida, Davis, and Colburn, (1976) in using span rather than the number of alternatives as a covariate with localization performance suggests that

the speaker span is the determining factor (page 691).

In summary, the studies reviewed in this section have made it clear that directional hearing acuity decreases as the stimulus source is moved from the front of the listener to the side. As well, it seems likely that speaker span is an important variable influencing localization accuracy.

<u>Elevation of sound source</u>. This final factor has not been as systematically investigated as the previous one, but two studies, Gardner and Gardner (1973a) and Wettschureck (1973), are suggestive of what happens to directional hearing performance in the vertical plane.

Gardner and Gardner (1973a) compared vertical localization at five azimuthal angles: 0, 5, 15, 45, and 90°. Fourteen listeners were tested on their ability to localize the position of a five voice recording of connected speech, presented from an overhead arch of nine loudspeakers. The speakers were spaced 22.5° apart, with speaker number one located at ear level directly ahead of the listener, and number nine directly behind at the same elevation. For other orientations, the listener's chair, located directly below the middle speaker, could be swivelled to bring the arch into the required plane. During testing, the speakers were activated in random order, the stimulus duration being 3.5 to 6 seconds. The results were reported by using an error index, with index values ranging from "0", representing a perfect score (all speakers correctly located) to "100" representing guessing. Gardner and Gardner found that as the orientation of the speaker arch was moved through each of the five azimuthal angles, the error index decreased. That is, at 0° the error index value was

62; at 5°, 53; at 15°, 30; at 45°, 15; and at 90°, 4. They concluded that localization accuracy increases from the median plane through to the transverse plane.

Wettschureck (1973) reported on the median plane only, his study dealing with MAA's. Using free-field conditions and listeners whose heads were held fixed in place, he calculated the difference limen for areas in front, above, and behind. He found that with a white noise source, MAA's in the front were 3.2°, from behind 4.3° and above 6° to 9°.

Although much remains unknown concerning difference limens for elevation at other orientations besides the median plane, the present section has indicated that MAA's in the vertical median plane increase with increasing elevation and that vertical directional hearing improves as the sources are moved from the median to the transverse plane.

Monaural Cue System

The existence of a directional hearing system based on only one ear has not been a popular hypothesis with auditory researchers. Gatehouse (1969) in his review of the monaural localization literature made explicit the obvious reason:

> The scientific investigation of sound localization ... has, since its earliest beginnings (Venturi, 1800a, 1800b; Weber, 1848; Weber, 1851), been premised upon the use of two ears. That is, the assumption has been made that accurate localization is not possible unless the organism doing the hearing and locating has an intact, two-sided neural and morphological system. (page 1)

As his review showed, however, there were several studies in the literature indicating that monaural listeners could locate sounds reasonably well. For example, from the clinical literature, Angel and Fite (1901a, 1901b), Klemm (1918), Jongkees and Veer (1957), and Palmer (1966) all showed that monaural listeners could perform adequately on at least some localization tasks, and similar results were found in the experimental literature—e.g., Jongkees and Groen (1946), Aase (1962) and Butler & Naunton (1967). But in his summarizing remarks on the literature as a whole, Gatehouse suggested that since monaural localization ability varied so widely across studies, the effects of monaurality on directional hearing could not be unequivocally stated.

Fisher and Freedman (1968a) also examined those studies showing monaural localization was possible and attempted to explain the phenomenon. They argued that binaural difference cues are neither necessary nor sufficient for accurate directional listening under all conditions, and the results of their study supported such a view. Thirteen subjects were tested on their ability to locate the position of a sounding speaker when it was positioned randomly at one of 16 positions around them. A boom arrangement located directly above the listener's chair allowed the loudspeaker to be moved to the required position, the spacing between positions being 22.5°. The subjects were tested under two conditions: (1) both ears unoccluded, and (2) right ear only occluded.[5] In both conditions, their heads were held in place by a headband assembly. Prior to testing in each condition, they were given a number of training trials. For these trials they received visual feedback after making their choice. During testing the subject used a number system to refer to stimulus positions, the stimulus being pulsed white noise. Each subject received 40 trials per condition. Fisher and Freedman found that the two conditions did not differ significantly as to size of errors, direction of errors, or percentage of error in either direction (A test). But they also noted that front-back confusions increased three-fold in the binaural condition. Because monaural performance had equalled binaural, they concluded that interaural difference cues are not a necessary condition for directional hearing; and, in addition because there were fewer front-back errors in the monaural case, they felt binaural cues are not a sufficient condition for accurate localization in all situations. Fisher and Freedman explained the results by suggesting that the pinna provided the necessary cues for the monaural listener, an explanation based on Batteau's (1967) pinna hypothesis theory.

As was indicated earlier (page 28), this theory (Batteau, 1967, 1968) may describe the mechanism for monaural localization. The fact that each pinna performs an angle dependent transformation leads to accuracy, but one transform is theoretically sufficient for an adequate level of position coding. It seems reasonable to suggest, then, that changes in sound spectrum due to pinna transform, i.e., intra-aural (within ear) spectral differences, can be considered one cue for monaural direction finding, a view favored by a number of researchers--e.g., Elfner, Bothe, and Simrall (1970), Gatehouse and Cox (1972), Searle et al. (1976).

Intra-aural amplitude difference is hypothesized to be the second cue, its psychological correlate being loudness difference. Perrott and Elfner (1968) made a careful study of both cues and concluded that loudness changes were the primary consideration in monaural localization in the horizontal plane. They found that six monaural listeners who were required to localize, without the help of head movements, either a white noise or 7 kHz pure tone presented randomly from a speaker at $\pm 45^{\circ}$ azimuth performed at better than chance levels and equally well on both stimuli. However, when the same subjects performed the task with the signals matched for sensation level (SL) at the two ears, they could localize at no better than chance levels when using either stimuli. Perrott and Elfner concluded that in the normal monaural situation, i.e., sounds not matched for SL, the monaural listener uses intra-aural loudness differences to localize. And when these differences are removed, performance drops. They suggested that had pinna generated spectral cues been operating in either the normal or SL condition, the white noise should have been better localized than the pure tone, which it was not.

To ascertain whether the listeners in the monaural SL condition could learn to utilize spectral cues, a second experiment was performed using the same testing paradigm. In this case, two of the original six subjects were given 80 localization trials in the monaural SL condition to obtain baseline performance. Following these trials, each subject was given an additional 80 trials with verbal feedback after each trial. One received veridical feedback, the other reversed, i.e., told the signal had come from the left when it had actually come from the right and vice-versa. It was found that both subjects were able to correctly localize by using spectral cues alone. Perrott and Elfner concluded that although intra-aural spectral differences are not of immediate use to the monaural listener, he or she can learn to utilize such cues with practice.

As was pointed out earlier (Batteau, 1968; Blauert, 1969/70), localization of elevated sources, at least in the median plane, appears to depend upon pinna transform. This should also hold true for the monaural case, based on an argument similar to that presented above for the horizontal plane.

The most convincing evidence that intra-aural spectral differences code for directional hearing in the median plane comes from Bloom (1977). He performed a psychophysical study to determine whether the sensitivity of the monaural auditory system paralleled the spectral changes produced by the pinna transform. Monaural minimum-audible-field (MAF) measurements were performed on five subjects by using an automated method of limits, monaurality being obtained by means of a cotton plug. Testing took place in an anechoic chamber, with the subject seated in a chair equipped with head stabilizing bars. MAF measurements were made for seven source elevations, -60, -45, -15, 0, +15, +45, and +60°, the interaural axis being 0°. The test signal center frequencies were spaced .5 kHz apart for the interval 4 kHz to 10 kHz, after which spacing went to 1 kHz, cut-off being reached at 16 kHz. All stimuli were delivered from a slightly modified ionophone transducer located in the lateral vertical plane containing the interaural axis. When the appropriate transformations of the data were made, Bloom found that the MAF functions generally paralleled those produced by the pinna transform for any given angle of incidence. He concluded that " ... the auditory system does indeed monaurally detect the spectral energy transformations produced by the pinna." (page 827).

In summary, two cues, intra-aural amplitude and spectral differences are known to be utilized by monaurals for horizontal plane localization, with amplitude differences suggested to be the more potent of the two. For an elevated source in the median plane, monaural directional hearing appears to depend on pinna transform.

Influencing Factors

In this section, the influence of six factors on monaural localization accuracy will be considered: (1) head movement, (2) pinnae occlusion, (3) stimulus complexity, (4) subject training, (5) azimuth of sound source, (6) elevation of sound source.

Head movement. It is typically assumed that a monaural listener can determine the location of an unfamiliar sound by moving his or her head in a scanning fashion to isolate the region of maximal stimulation (Elfner, Bothe, & Simrall, 1970). Such a view is supported by the work of Butler, Naughton, Neff, and Strominger (1960). They found that subjects made artificially monaural had difficulty accurately localizing wide band noise when their head movements were restricted. With head movements, however, their accuracy improved.

Aase (1962) reported similar results using listeners who had one ear covered with an industrial ear protector. The subjects were required to localize a wide band noise randomly presented from various positions in the horizontal plane of the front quadrant. It was found that monaural performance could approach that of binaural when any type of head and/or trunk movement was allowed in conjunction with knowledge of results.

Butler (1969b) tested monaural listeners on their ability to localize broad band noise bursts in the vertical plane with and without head movements. The stimulus was presented randomly from one of five speakers arranged in a vertical column, each speaker separated by 15°, starting at 27° below eye level. He found that swiveling the listener's chair 90° to the left or right did not improve performance on the task over the stationary condition.

In contrast to the first two studies reviewed but in agreement with the third, Gatehouse and Cox (1972) found head movements did not help monaural listeners on horizontal and vertical plane localization. In this study, to be reviewed later, the subjects were not expressly told to move their heads, which may explain the lack of effect.

In summary, these reports suggest that monaural listeners may benefit from head movements during horizontal-plane localization, but such movements appear to have little influence in the vertical plane. The need for additional research in this area is obvious.

<u>Pinnae occlusion</u>. Like the previous topic, pinnae occlusion has not been sufficiently examined for the monaural case. The author is aware of only two studies referring to such manipulations. In the first, Gilse and Roelofs (1930), reviewed by Butler (1975), the experimenters serving as their own subjects localized an impulse sound, resembling the ticking of a watch, presented from sources located at 0, 20, 40, 60, and 80° azimuth in the horizontal plane. Testing themselves monaurally, Gilse and Roelofs reported that the stimulus appeared to come from a more restricted region of the presentation arc when the convolutions of the pinna were filled with Plasticene than when they were left open.

In the second study conducted by Butler (1975), a university student, monaural from birth, was tested on his ability to localize white noise bursts presented randomly from one of nine equally spaced loudspeakers located in the left, front quadrant (i.e., 0^{o} to 280^{o}), the side of the normal ear. The subject was tested first with his pinna in its normal position and then when it was bent forward and taped to the cheek; in both cases head movement was restricted. Butler found localization performance was best for the unaltered pinna, and in agreement with Gilse and Roelof's results, distorting the pinna tended to limit responses to a narrow region of the speaker arc between approximately 335 and 310 degrees.

From these experimental results it appears that pinna distortion is detrimental to monaural localization, with the resulting perception of sound locus being limited to a narrow region of the speaker span.

Stimulus complexity. In a series of four studies, Butler (1971), Belendiuk and Butler (1975), Butler and Planert (1976), and Belendiuk and Butler (1977), Butler and his associates have clearly illustrated the influence of stimulus band width on monaural localization in both the median plane and front quadrant of the horizontal plane.

Butler (1971) examined the ability of monaural listeners to localize the position of pure tone bursts presented from behind a horizontal, semicircular screen numbered into 17 sections, starting with "1" directly in front of the listener and progressing through numbers "2" to "9" on either side. Tone bursts of nine different frequencies were presented from a loudspeaker located behind section number "1", the subject's task being to report the number of the section from which the burst appeared to emanate. The results showed that almost without exception, the tones were perceived to come from the side of the unoccluded ear, with the amount of displacement from mid-line varying across frequencies--e.g., for .25, .4, .6, .9, 1.4, 2.0, 3.2, 4.8 and 7.2 kHz tone bursts, the displacements were respectively, 43, 44, 45, 55, 57, 57, 48, 47, and 63°. Butler concluded that under these conditions of test, monaural localization judgments bore no consistent relationship to objective position.

In the next study of the series, Belendiuk and Butler (1975) tested the effects of low-pass noise bands on monaural directional hearing in the horizontal plane. Listeners made monaural in the right ear by means of an earplug and muff arrangement were required to localize stimuli presented from four loudspeakers located on their left at 345, 330, 315, and 285°. There were four test stimuli, three low-pass noise bursts with cut-offs at 1.0, 4.0, and 8.0 kHz, and broad-band noise. The subjects were asked to avoid moving their heads during testing. It was found that localization was poor for the 1.0 kHz and 4.0 kHz low-pass stimuli but improved abruptly for the 8 kHz, and was best for the broad-band noise. Based on these and other findings, Belendiuk and Butler concluded that frequencies above 5 kHz must be present in a sound if it is to be accurately localized monaurally in the horizontal plane.

In the third report, Butler and Planert (1976) studied monaural directional hearing in the vertical median plane. The monaural subjects were required to localize five, 8 kHz centered bandwidth stimuli and broadband noise, the five bandwidths being 6.0, 5.0, 4.0, 3.0 and 2.0 kHz. Monaurality was achieved as in the previous experiment (Belendiuk & Butler, 1975). The stimuli were presented from five loudspeakers spaced 15° apart in the listener's median plane, the first positioned at -30^{o}, the fifth at $+30^{o}$ re interaural axis. It was found that as the 8 kHz centered bands were increased from a 2 kHz bandwidth to 6 kHz then to broadband, the localization performance improved monotonically. The authors concluded that for monaural listeners, stimuli which encompass more of the higher audio frequencies provide more complete spectral cues.

For the final report of this series, Belendiuk and Butler (1977) examined in more detail the spectral cues required for monaural, horizontal plane localization, the testing paradigm being identical to that used by Belendiuk and Butler (1975). Based on the performance of seven listeners who were tested on a total of 17 different stimulus combinations, Belendiuk and Butler reached the following conclusions:

> In general, proficiency in locating sounds monaurally in the horizontal plane improved with increases in the bandwidth of the stimulus. But, as shown by Butler and Planert (1976) and confirmed by the present study, accuracy on this task does not improve in an orderly manner as the bandwidth is augmented. In many cases, increased bandwidth resulted in a decrement in localization performance, and this is the point that most concerns us. What may be happening is that different individuals utilize different and restricted frequency regions of the sound spectrum for locating sounds monaurally. (page. 357).

From these four studies the following conclusions may be drawn for the monaural case: (1) Pure tone, horizontal plane localization in the front quadrant is not related to objective position. (2) Frequencies above 5 kHz must be present for accurate horizontal localization, but individual listeners do not utilize the higher frequencies to the same degree. (3) Broadband stimuli are necessary for accurate vertical localization in the front, median plane.

<u>Subject training</u>. The influence of this fourth factor on monaural localization has been well established in a number of studies—e.g., Bauer, Matuzsa, Blackmer & Glucksberg (1966) and Perrott & Elfner (1968).

Bauer et al. (1966) examined the ability of subjects made monaural by means of an earplug to adapt to the monaural condition. In the first experiment, two subjects each wore a V51-R plug for three days, during which time they were tested at six hour intervals on a localization task. Testing took place in an anechoic chamber, with the subject required to localize the position of either a continuous or intermittent white noise stimulus presented from one of 20 loud-speakers located in the frontal quadrant. It was found that one subject required 65 hours the other 67 hours before he could perform the localization task at a level comparable to pre-plug insertion.

In the second experiment of the report, six subjects wore a V51-R earplug in one ear, but they remained in the anechoic chamber for training-test sessions, with training consisting of visual feed-back (i.e., a small light was turned on at the correct azimuth) following each localization trial. Bauer et al. found that after receiving from four to nine training sessions over a period of five hours, four of the listeners had reached their pre-plug insertion scores on the localization task. From these two experiments, they concluded that humans can adapt to distorted localization cues after about three days, but this period can be reduced to a half-day with specific training.

In a paper by Perrott and Elfner (1968) reviewed earlier (page 54), one of their experiments indicated the value of training for the monaural case. The test apparatus and procedure were the same as before except the monaural listeners received 40 training trials prior to testing. During these trials a light signalled whether the speaker choice had been correct. When the results of this experiment were compared to the same listeners' performances in a previous experiment, it was found that the median number of localization errors went from approximately 15 for the no training condition to zero for the training condition. Perrott and Elfner also found the trained monaurals performed as well as the untrained binaurals.

The effect of training on vertical localization has also been assessed for the monaural listener. Hebrank and Wright (1974a) tested the ability of 10 monaural subjects to localize the position of a white noise stimulus (flat-spectrum noise) presented from one of nine positions in the median plane. These positions were spaced 30° apart, starting from -30° in the front and terminating at -30° in the back. Subjects were first given 27 localization trials without feedback, then four blocks of 27 trials with feedback (i.e., lights on the subject's response panel indicated the correct sound locus). Hebrank and Wright found that prior to receiving knowledge of results, the subjects correctly localized 40% of the stimulus presentations. With feedback this figure rose to 60%.

In a brief statement, Yorifuji, Morimoto, and Ando (1975) reported a similar finding concerning the effect of training on localization in the median plane. Although no details were given, they made the following statement: "When normally binaural subjects are made monaural by occluding one of the ears, the localization errors increase at the beginning and decrease after temporary training." (page 537).

In summary, it appears that training will improve the directional hearing accuracy of monaural listeners in both the median plane and frontal quadrant of the horizontal plane.

Azimuth of sound source. One effect of stimulus azimuth is a tendency for sounds located on the side of the plugged ear to be displaced towards the unplugged side. Gatehouse (1969) in his review of the non-clinical literature found this effect was often reported--e.g., Ferree & Collins (1911), Bauer et al. (1966) and Butler & Naunton (1967).

The Butler and Naunton (1967) study nicely illustrates the phenomenon. They had monaural subjects locate the position of a broadband noise burst presented from speakers located in the frontal quadrant. Monaural hearing was obtained by use of an industrial ear muff, and head movements were restricted by a headrest. The results showed that for a stimulus presentation level of 30 dB SL, a noise-burst presented from the monaural side at 0, 20, 40, 60, and 80° was perceived to be at, respectively, 346, 352, 10, 20, and 28°; whereas, the same presentation angles on the unplugged side produced the following: 26, 34, 42, 59, and 75°, respectively.

Not all researchers have noted the effect, however. Fisher and Freedman (1968a), whose study was reviewed earlier (page 53), made the following statement concerning their results:

> Contrary to the findings of other investigators ... our subjects manifested no consistent or significant shifts toward the side of the unoccluded ear that were not also

> evident when neither ear was occluded. In fact, the only comparison for size and direction of error that was significant in the REO [right ear occluded] condition was that larger rearward errors were measured on the side of the unoccluded ear. This may be considered a shift away from the more sensitive ear. (page 218).

Harris and Sergeant (1971) suggested Fisher and Freedman's results were due to the nature of the stimulus, i.e., brief noise-burst trains, but much more is probably involved--e.g., training, stimulus duration, and task difficulty.

Harris and Sergeant (1971) have determined monaural MAA (monaurality achieved by an earplug and a circumaural muff) for two angles, 0° and 60°, in the horizontal plane (see page 45). Testing was done using a moving source located on the side of the unoccluded ear, the stimuli being four pure tones (0.8, 1.6, 3.2 and 6.4 kHz) and white noise. At 0°, the MAA's were approximately 4, 7, 6, 8, and 3.5°, respectively, for 0.8 kHz, 1.6 kHz, 3.2 kHz, 6.4 kHz and white noise. And at 60°, they were > 12, 11, 8.5, 11, and 3° respectively for the same stimulus series. It appears then, that like the binaural case, acuity for monaurals decreases as the reference source moves away from the median plane.

This section has indicated that monaurals generally refer sounds to their unplugged side, but exceptions do occur. These have not been adequately explained. In addition, monaural acuity decreases as the source is moved off the median plane toward the side of the unplugged ear. MAA's have not been reported for the occluded side.

Elevation of sound source. Elevation of a sound stimulus, the final factor, has a similar influence on sound location for monaurals as does azimuthal position: sounds located in the median plane are displaced towards the open ear (Butler, 1969b; Gardner, 1973b).

Butler in a second experiment reported in the 1969b study (page 57) used the same apparatus as before to test the localization performance of 18 monaural subjects on midline, elevated sounds. There were three stimulus conditions: Condition 1, broadband noise; Condition 2, 3.8 kHz low-pass noise; and Condition 3, 2.2 kHz low-pass noise--9.0 kHz high-pass noise (band-reject). It was found that 8, 10, and 13 subjects, respectively, in Conditions 1, 2, and 3 reported that a noise burst on one or more trials appeared to be displaced towards the unoccluded ear. However, the error size for these subjects was no different than for those who did not perceive displacements.

Gardner (1973b) reported a similar finding for monaural listeners localizing wide-band noise presented from the anterior sector of the median plane:

> Should one ear now be completely blocked off so that no signal at all reaches the canal of that ear, the median, or frontal plane aspect of image position may undergo a very noticeable rotation toward the side of the open ear. Such rotations can be as large as 90°, in which case correct identification of the vertical position of the loudspeaker source in use becomes extremely difficult. (page 1491).

Unfortunately there are no monaural acuity studies dealing with elevated sources. This is yet another area where research is required.

In summary, sources in the anterior median plane may be displaced toward the unoccluded ear. Research on other orientations besides this plane is required, and acuity studies for elevated sources are necessary.

Horizontal Localization: Monaural versus Binaural

Given that we have a monaural and binaural cue system, the relative accuracy of the two is of some theoretical concern. If, for example, the monaural system can provide the listener with a degree of accuracy which, for practical purposes, is no different from the binaural, the traditional view that a listener requires two functional ears needs rethinking. Searle et al. (1976) have taken a signal step in breaking with this tradition by not only suggesting that four of the known static localization cues can be assigned relative levels of accuracy, but also by suggesting that under certain conditions (abnormal conditions, as they refer to them) some localization cues may be abnormally accurate or abnormally inaccurate. The implication of the latter suggestion for monaural listening is apparent: What are the characteristics of those situations where monaurals can perform directional hearing tasks at a level comparable to that of binaurals? It is this question that many researchers have not adequately considered when constructing theoretical arguments on the necessity of binaural stimulation. They have shown the existence of a monaural cue system, they have manipulated some of the variables which affect it, but they have only started to consider what variables and what levels of these variables must be present for intra-aural cues to be as efficacious as interaural.

In this section and the next, some of the reports comparing monaural and binaural localization performance are reviewed, with the purpose of showing how the four variables outlined earlier, (1) stimulus azimuthal angle, (2) stimulus elevation, (3) pretest training, and (4) head position, have been allowed in many cases to assume different levels from study to study. And this being the case, the accuracy of monaural localization with respect to binaural will understandably fluctuate across experiments.

Five studies were mentioned in the introduction to illustrate the inconsistencies in results for the horizontal plane case: Fisher and Freedman (1968a), Perrott and Elfner (1968), Batteau (1968), Gatehouse and Cox (1972), and Russell (1976).

The Fisher and Freedman (1968a) research, showing monaurals can localize as accurately as binaurals, has been described (page 53). It remains then to consider how they manipulated the four variables of concern to the present study. There were 16 levels of the azimuthal angle, each 22.5° apart with the elevation factor held constant, all sources being located in the horizontal plane at the level of the interaural axis. All subjects received training with feedback, but the number of such trials per subject was not reported. It is of interest that each listener was trained on all 16 positions, but tested on only eight. Head movements were restricted by means of a headband.

Although not a manipulated variable in the present study, stimulus duration is also of interest in these reports. In the above case, the sound remained on until the subject made a response.

Perrott and Elfner (1968) also found that monaural localization accuracy could equal binaural (page 63). There were two levels of the training factor: binaurals receiving no training, the monaurals, 40 trials with visual feedback. Azimuthal angle of the sound source had two levels $\pm 40^{\circ}$ re the interaural axis. The head position factor, like the elevation variable, was also held constant, with the apparatus designed to supposedly eliminate the benefit derived from any such movements. That is, the two speakers were attached directly to the listener's head by means of a headband assembly. Stimulus duration was 1 second.

Using tape recorded speech as a stimulus, Batteau (1968) reported that monaurals were not as accurate as binaurals on a horizontal plane localization task. The azimuth variable had eight levels, speakers being positioned every 45° on a 3.7 m diameter circle traced around the listener. Elevation of the source was held constant, but the level of the speakers re the subject's interaural axis was not specified. The subjects' experience with localization tasks was not mentioned, suggesting that the training variable had gone uncontrolled. Also going uncontrolled was the head position factor. In this case, the subjects were free to move their heads if they chose to do so. Batteau did not report on stimulus duration.

Gatehouse and Cox (1972) found that a binaural group of eight subjects were significantly superior on horizontal plane localization than were a group of 8 monaural 'severe' to 'profoundly' sensorineural deaf subjects to which they were matched. Both groups were tested on eight levels of the azimuth variable, each angle being 45°, starting from 0° in the front, median plane. The subjects received five different elevations, 0, ± 15, $\pm 30^{\circ}$ re the interaural axis, but owing to the nature of the experimental design, the azimuth by elevation interaction could not be examined and both variables were therefore analyzed by separate analysis of variance. The head position factor had two levels. All subjects received two blocks of trials with their heads fixed and two with heads free to move. However, the subjects were not specifically instructed to move their heads during the head free trials, which may be one reason Gatehouse and Cox found head movements had no effect on localization. But they did find that the binaural group had five times as many front-back confusions as the monaurals, a result similar to that reported by Fisher and Freedman (1968a). Neither the monaurals nor binaurals were trained for the localization task, although five practice trials were given to each subject. The fact that the monaurals in this study were not "artificially" created as they were in the above three studies suggests that the subject training variable was essentially fixed at a different level than in the above studies. The stimulus was a white noise burst, 10 per sec for 3 seconds.

Using a 1.5 sec duration, broadband white noise stimulus, Russell (1976) tested monaural and binaural listeners on a horizontal plane localization task and found the monaurals were clearly inferior. The loudspeakers were arranged in 22.5° intervals, starting from 0° in the front and progressing around the right side of the listener (the non-occluded side for monaurals) to 180° behind, a total of nine levels of the azimuth variable. Elevation was held constant at 0° _re_ interaural axis, and the subject training variable was not manipulated, the listener going directly into the test situation. Head movements were held constant by means of a headrest.

Looking at these studies, it can be seen that with respect to the four variables of concern, there are noticeable differences between those studies suggesting accurate monaural localization is possible and those suggesting otherwise. Artificially created monaurals apparently require some training according to the results of the first two studies, yet Gatehouse and Cox (1972) tested long term monaurals and found their performance inferior to binaurals. This seems surprising for these subjects had ample opportunity to adapt to their loss. Batteau (1968) appears not to have controlled for the training variable, and Russell (1976) did not examine it, concluding that " ... two ears are still better than one" (page 70). Head movements were held constant in the Fisher and Freedman (1968a) study and possibly in the Perrott and Elfner (1968) report, but Batteau did not control for them, and Gatehouse and Cox (1972) were probably unsuccessful in their manipulation of this variable. Elevation remained constant at the same value (0^{o} re interaural axis) in three studies, with Gatehouse and Cox (1972) examining five levels and Batteau (1968) apparently allowing the factor to vary across subjects. The azimuthal angle was varied from 2 to 16 levels, the important consideration here being the resulting changes in speaker span and span location. Also of note is the fact that each study used a different signal duration.

Vertical Localization: Monaural versus Binaural

For this plane, six studies were mentioned in the introduction to illustrate the inconsistencies which appear across studies with respect to monaural versus binaural localization accuracy: Butler (1969b), Gardner (1973b), Butler and Planert (1976), Bothe and Elfner (1972), Gatehouse and Cox (1972), and Hebrank and Wright (1974a).

Butler (1969b) tested subjects in both monaural and binaural conditions on a vertical localization task and reported the binaural condition superior. There were five levels of the elevation variable, with the speakers separated by 15°, starting from 27° below eye level. Azimuthal angle was held constant at 0°, i.e., the front, median plane. Both head position and training were held constant: the listener's head was steadied by a headrest and he or she received no training trials. The stimulus, various noise bursts, remained on until the subject made a response.

Gardner (1973b) systematically covered sections of the pinna's surface until monaurality was achieved and found that subjects receiving this treatment showed an increasing number of errors on a vertical localization task, compared to binaurals, as the extent of pinna coverage increased. Nine levels of the elevation variable were used, starting at 18° below eye level and proceeding in 4.5° steps. The remaining three variables were all held constant: (1) The speaker arc was placed in the front, median plane, (2) Head movements were restricted by a headrest, and (3) No training was provided. The stimulus consisted of three noise bursts, each 1 sec in duration.

Butler and Planert (1976) in a study reviewed earlier (page 60) reported that monaurals were inferior to binaurals on every bandwidth tested in the localization task. The azimuthal variable was held constant at the frontal, median plane, but there were five levels of the elevation factor, each separated by 15°, starting at -30° *re* interaural axis. The training variable was unintentionally manipulated, favoring the binaural condition. Subjects were given 50 test trials on the localization task for screening purposes and then a further 50 binaural trials before testing " ... to reduce the influence of practice on the results of the main study." (page 104). No such practice trials were mentioned for the monaural condition, the study being a within-subjects design. Head movements were held constant by use of a head rest. The stimulus remained on until the listener made a speaker choice.

Using a vertical localization task, Bothe and Elfner (1972) reported that subjects tested in both a monaural and binaural mode had similar localization scores in both conditions. The sources were separated by 30°, with one at the level of the interaural axis, the second above it. Azimuth was held constant at 0° in the front, median plane. Head movements were restricted by a bite bar, and no training was given. Stimulus duration was .5 sec of wideband noise. It is of interest in this study that after the third block of 40 trials, monaural accuracy began to decrease while binaural rose. Prior to this there had been no significant difference between the two conditions. The authors interpreted this as a boredom effect.

Gatehouse and Cox (1972), the study outlined in the previous section, found no significant difference between monaurals and binaurals on vertical plane localization. It will be recalled that they used five elevations and eight azimuthal angles, the elevation factor being assessed by collapsing across angles at each of the five levels of the elevation factor. As in the horizontal case, head movements were of no value. But the same comment applies here as was given earlier: The listeners were not explicitly instructed to move their heads.

In the study discussed earlier (page 63), Hebrank and Wright (1974a) reported that monaural listeners could be trained in approximately 100 trials to match their binaural scores, the latter being obtained without training. Briefly outlining the study again, there were nine levels of the elevation factor, allowing complete coverage of the median plane from -30° anterior to -30° posterior. Head movements were restricted by a head clamp assembly. Stimulus duration was eight seconds.

As was the case for the horizontal plane, the researchers showing monaurals can perform as well as binaurals treat the four factors differently than do those showing monaurals are inferior. For example, the first three studies, suggesting binaural localization is superior, generally hold azimuth, head position, and training constant; whereas, the remaining three have, between them, manipulated all three variables. It is also of interest that Bothe and Elfner (1972), whose study most resembles the first three reports with respect to the variables held constant, contradicts those findings. This may simply be due, of course, to the fact that only two levels of the elevation variable were examined, making the localization task a relatively simple one.

It was mentioned in the introduction that the results of the present study were anticipated to be of value for modeling attempts such as that of Searle et al. (1976). To conclude this review, a brief discussion of that model will be given, and the utility of the present report for such theorizing will be outlined.

Searle et al. (1976) have attempted to depict the human auditory localization task in terms of a mathematical model based on statistical decision theory. To accomplish this, they represent the known localization cues as Gaussion random variables, an assumption which allows the interactions among the cues to be analyzed in a fashion similar to that found in signal detection theory. Not only can the cue interactions be analyzed, they can also be predicted, allowing the researcher to determine beforehand the complete pattern of responses an observer will display during a pointing experiment in sound localization. Although this is an exciting development for auditory research, the model is limited to sources in the front quadrant of the horizontal plane and to elevations not exceeding 90° in the vertical, median plane. Searle et al. ~~point~~ out the reason a more general case has not been developed:

> Unfortunately, most of the localization experiments reported in the literature have sound sources restricted to either the front quadrant of the horizontal plane or the upper vertical median plane, so verification of [the] general formulation of the localization model will have to await further experimentation. (page 1165).

The present study attempted to rectify this deficiency by extending localization decisions to all four quadrants at three levels of elevation. In addition, the inclusion of a head movement variable was expected to provide data for models dealing with both dynamic and static cue systems, the Searle et al. model being able to handle only static.

Throughout this review the influence of head movement, subject training, stimulus azimuthal angle, and stimulus elevation on monaural and binaural cue systems has been clearly indicated where enough data were available to make an assessment. It is also evident from the last two sections of the review that these variables are not adequately controlled in localization research, given their potential to affect the accuracy of directional hearing. Based on these considerations, it seems reasonable to suggest that the accuracy of monaural with respect to binaural localization will fluctuate as these variables are allowed to interact and assume different levels across studies. Therefore, if the utility of the monaural cue system is to be unequivocally determined, these variables must be manipulated simultaneously in a single experiment. Rarely, however, has the monaural/binaural comparison been made using a factorial design, and in the most widely referred to case (Gatehouse & Cox, 1972), the interactions could not be analyzed. It was the general purpose of this study, then, to assess the monaural versus binaural comparison by using a factorial design to isolate the interactive effects of the four cues. Although the study was exploratory in the sense that there are no published reports dealing with 360° of speaker span and multiple variables on which to base predictions, the following hypotheses based on the more limited cases reported in the review were advanced:

(1) Trained monaurals with fixed heads will have fewer front-back reversals than trained binaurals with fixed heads. This hypothesis follows directly from the work of Fisher and Freedman (1968a) and Gatehouse and Cox (1972). In both of these studies monaurals had fewer front-back errors on a 360° localization task than binaurals.

(2) Trained monaurals with fixed heads will not differ significantly with respect to front-back reversals from trained or untrained binaurals allowed head movements. This hypothesis is based on Thurlow and Runge's (1967) finding that head movements decreased front-back confusions for binaurals. It is anticipated that monaurals will still perform adequately.

(3) Trained monaurals with fixed heads will perform as well on the localization task at all elevations as trained binaurals with fixed heads. Fisher and Freedman (1968a) tested a similar hypothesis at 0° re interaural axis and found the two groups performed equally well.
(4) Trained monaurals with fixed heads will be no more inaccurate on their occluded side than are trained binaurals with fixed heads. This hypothesis follows from Fisher and Freedman (1968a) who showed trained monaurals do not displace sounds to the unoccluded side in a 360° speaker span localization task.
(5) Finally, it is hypothesized that trained monaurals allowed head movements will localize as well in the frontal quadrant (i.e., between $\pm 45^{\circ}$) as untrained binaurals allowed head movements. This hypothesis follows from the studies of Aase (1962) and Perrott and Elfner (1968) which showed that training monaurals or allowing them to move their heads improved their accuracy with respect to binaurals.

Chapter II

Method

Subjects

The subjects were 72, normal hearing, volunteer students (22 males and 50 females, with a mean age of 24 and 23 years, respectively) solicited from psychology classes at the University of Guelph. All were given a standard audiometric test (.25 to 8 kHz) at the start of the experiment, and those with gross hearing abnormalities (ISO, 1964 standards) were excluded.

Apparatus

Test chamber. The localization apparatus was housed and testing took place in a (3.96 m x 3.96 m x 3.04 m) sound treated room. The walls and floors of the room were covered with commercial, indoor-outdoor, foam-backed carpeting, which had for practical purposes the effect of attenuating sound by approximately 35 dBA across the frequency range of .25 to > 4 kHz (see Nanson & Slater, 1974; Nute & Slater, 1973). Together with the wall board, the insulation behind it, and the acoustic ceiling tile, the room thus had some degree of sound insulation. Heavy curtain material separated the testing and sound generating apparatus from the rest of the room which contained a desk and a filing cabinet.

Localization apparatus. Part of the localization apparatus consisted of a height-adjustable, pedestal chair having a footrest just above its base (see Figure 1). The chair was placed at the centre of an imaginary clock face marked out on the floor with 12 strips of masking tape, each strip separated from the other by 30° and labelled in large characters with the appropriate number. The seat

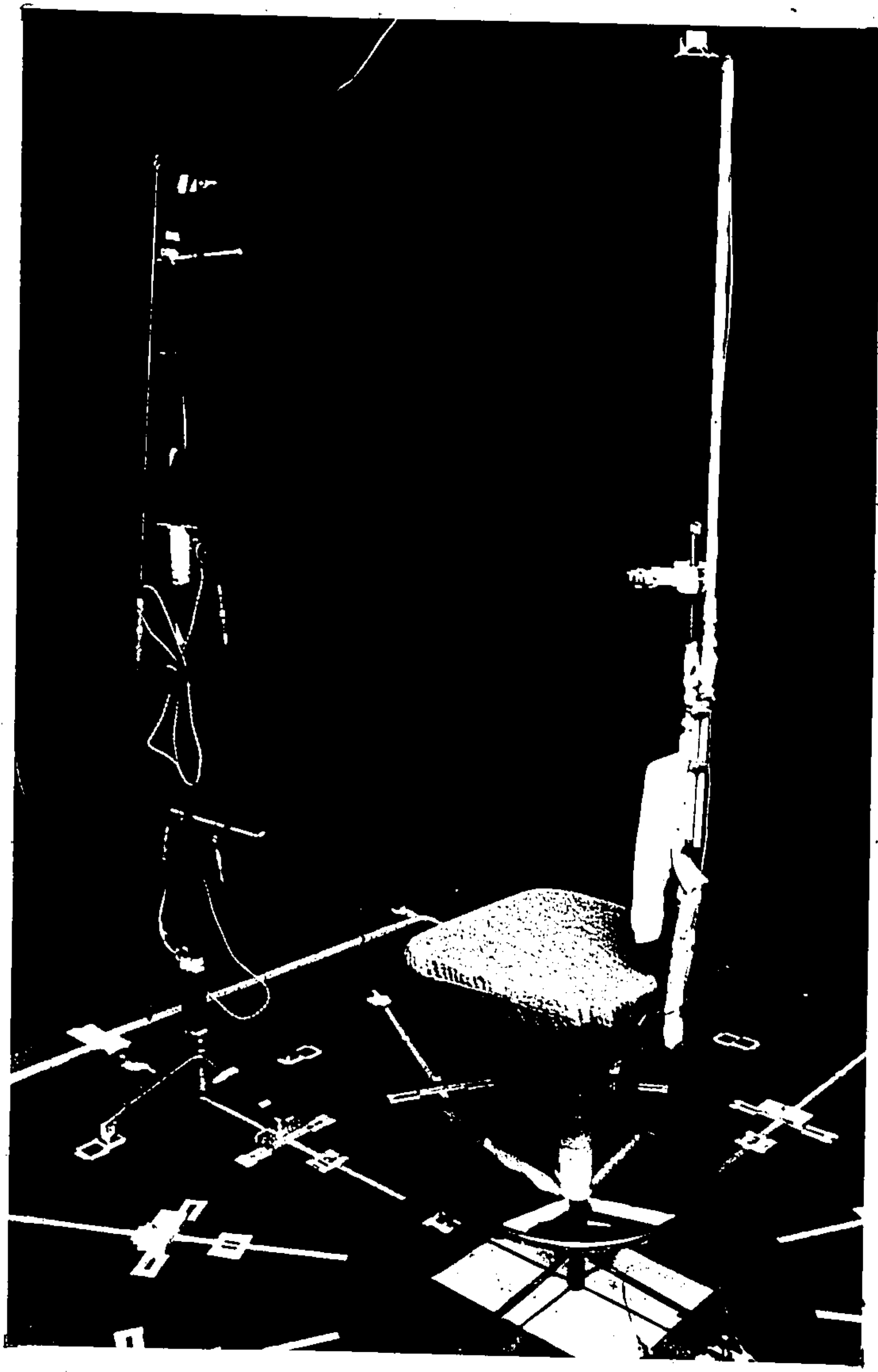

Figure 1. Localization apparatus.

of the chair was designed so that it could be locked facing the 12 o'clock position. Attached to the rear of the seat was a .91 m x 2.54 cm x 6.34 mm steel bar. Approximately 7.62 cm up from the seat level on this rod was a padded back rest (30.48 cm x 12.70 cm x 5.08 cm), and at its top extent was a front-facing metal yoke onto which the two 14 cm x 2 cm x 1.5 mm aluminum arms attached to either side of an adjustable, plastic headband (from a commercial hard hat) could be joined. Directly above (1.54 m) the chair seat was a speaker (Marsland) which was supported by a length of wooden dowel attached to the back rest.

The remaining part of the localization apparatus consisted of a 2.20 m high steel mast mounted on a four-legged metal base (see Figure 1). The mast had three aluminum rods projecting horizontally from it, each rod being tapped at the end to allow for the attachment of the stimulus speaker (Telephonics, TDH-49). The rods were adjusted so that when the subject's interaural axis was raised or lowered (by means of the adjustable chair) to the level of the middle rod (i.e., 0° elevation), a speaker attached to the upper or lower rod formed an angle of $+30^{\circ}$ or -30°, respectively, with reference to the centre of the subject's interaural axis. The distance from the centre of the interaural axis to the face of the speaker when it was located at one of the three elevations (i.e., 0° or $\pm 30^{\circ}$) and the speaker mast positioned at any one of the 12 clock-face positions was 1.06m. The mast could be easily carried without noise, and raised templates on the floor allowed it to be positioned accurately.

<u>Sound generating apparatus</u>. The sound generating apparatus, schematized in Figure 2 was rack mounted in one corner of the room.

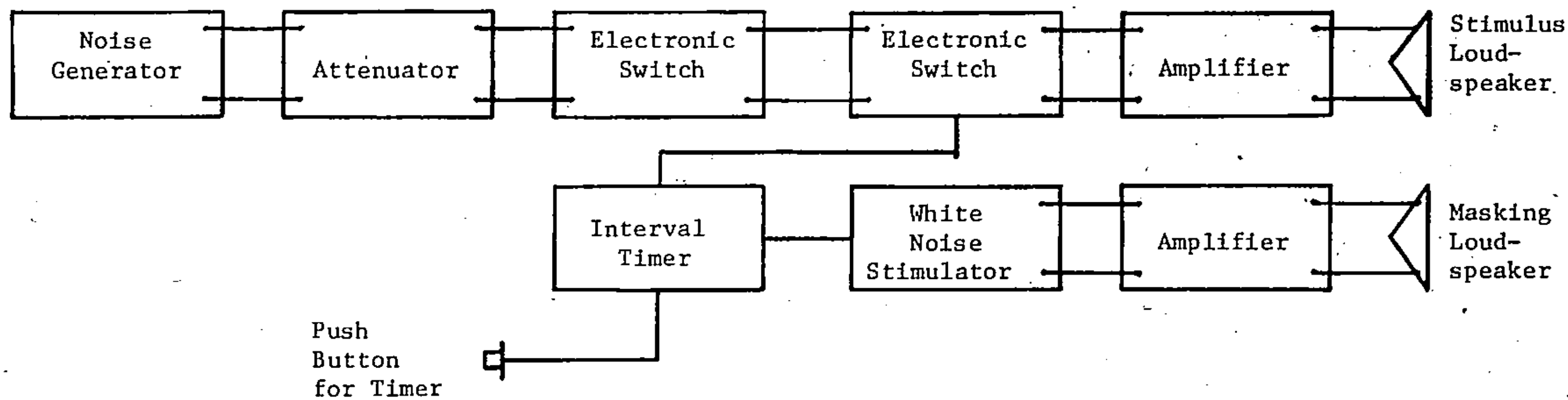

Figure 2. Block diagram of the sound generating apparatus.

The signal to be localized, a 20 kHz bandwidth, white noise (pulsed 10 times per second with a duty cycle of 50% and a rise/fall time of 4 msec) was produced by a noise generator (Grason-Stadler, Model 455C) then passed through an attenuator (Hewlett Packard, 3500 Attenuator Set) to an electronic switch (Grason-Stadler, Model 829E) where it was shaped. A second electronic switch (Grason-Stadler, Model 829E) connected to an interval timer (built by technicians of the Psychology Department), timed the signal which was then amplified (Sansui, Model AU-999) and fed to the speaker located on the mast.

A masking stimulus, white noise, was produced by a white noise stimulator (Lafayette, Model 1432), timed by the interval timer, then amplified (Philips Stero, Type 22 GH925/42 PL) and fed to the speaker located above the subject's chair. The sound pressure level of the masker at the approximate level of the subject's interaural axis was maintained between 80 and 82 dB SPL using a sound level meter (Bruel & Kjaer, Type 2204) fitted with an omnidirectional microphone (Bruel & Kjaer, Type 4135, 6.35 mm).

Other apparatus. An audiometer (Beltone, Model 15CX) was used to measure hearing thresholds.

A modified pair of ear muffs (MSA, Mark IV) and ear plugs (MSA, Accu-Fit^{TM}) were used at various stages throughout the experiment. The muffs were modified by removing one of them from the band and then connecting this muff to the end of an earphone headband of the type used for audiometric testing. With this arrangement both muffs could be placed on the subject, and then one of them removed without disturbing the other. The end of the band not connected to the muff rested on the plastic headband (from the hard hat), thus eliminating any concentrated pressure on the side of the head. Subjects found the modified muffs reasonably comfortable.

Design and Controls

A 2 x 2 x 3 x 2 x 12 factorial design with complete, intragroup counterbalancing to minimize sequencing effects (see Figure 3) was used as follows:

Between-block factors.

(1) Hearing Condition: Monaural, Binaural

Equal numbers of subjects were randomly assigned to the monaural and binaural levels, 36 subjects to each.

(2) Pretest Training: No-Training, Training

For both the monaural and binaural condition, 36 subjects were randomly assigned to one of the two pretest training levels (no-training, training), with 18 subjects to each level.

(3) Elevation: 0, $\pm$ 30°

Finally, the 18 subjects in each training condition were randomly assigned to one of the three elevation levels 0°, $\pm$ 30°, with 6 subjects per level.

Within-block factors.

(1) Head Movement: Head Fixed, Head Rotate

Three randomly chosen subjects from each of the 12 treatment combination cells (2 x 2 x 3) were tested with head fixed in Phases I and II of the experiment and then with head rotate in Phases III and IV. The remaining three subjects in the cell received the reverse order.

Hearing Condition	Pretest	Elevation	Head Fixed A_1 A_2 A_3 A_4 A_5 A_6 A_7 A_8 A_9 A_{10} A_{11} A_{12}	Head Rotate A_1 A_2 A_3 A_4 A_5 A_6 A_7 A_8 A_9 A_{10} A_{11} A_{12}
Monaural	Training	$+30^o$	S_1	
		0^o	S_2	
		-30^o	S_3	
	No-training	$+30^o$	S_4	
		0^o	S_5	
		-30^o	S_6	
Binaural	Training	$+30^o$	S_7	
		0^o	S_8	
		-30^o	S_9	
	No-training	$+30^o$	S_{10}	
		0^o	S_{11}	
		-30^o	S_{12}	

Figure 3. Block diagram of the factorial design. Hearing Condition (monaural, binaural), Pretest Training (training, no-training) and Elevation (+30, 0, and -30^o) are between-block factors; Head Movement (head fixed, head rotate) and Azimuth (30, 60...0^o, i.e., A_1, A_2...A_{12}) are within-block factors. Each cell (S_1 to S_{12}) contains 6 subjects.

(2) Azimuthal Position

Twelve 30^{o}, azimuthal positions ($30, 60...0^{o}$, i.e., A_1, A_2...A_{12}) were used. The sequence in which these azimuths appeared as the location for stimulus presentation was randomized for each subject with the stipulation that no position could occur twice during a block of 12 trials.

Dependent Measure. The error scores in degrees, i.e., the number of degrees away from the true source the subject's choice was located, formed the basis of the ANOVA. For example, if the correct azimuthal position was 60^{o} and the subject indicated 150^{o}, the error score would be 90^{o}.

Procedure

Prior to each testing session, the experimenter checked the sound pressure level of the white noise masker to ensure that no variations occurred between sessions. In addition, he switched the speaker to the appropriate elevation ($0, \pm 30^{o}$) for the incoming subject. Upon entering the room the subject was seated and biographical information (name, age, sex, hearing problems, handedness, and hair length, re: pinnae) was recorded. Next, the standard audiometric test was administered. Following this, the subject was taken and seated in the testing apparatus, the curtains were drawn, and the following instructions given by the experimenter:

> During the experiment, I'd like you to keep your feet on this foot rest. Please try to keep your feet in the same position on the rest throughout the experiment. This padded bar is here to provide support for your back, but try not to lean too heavily on it as this will create a tendency for your body to rock

backward and forward, a movement which could spoil the experimental results. If you will sit up straight against the back rest, I would like to measure from your right ear to this vertical mast. Now, if you will please stand up briefly, I'll adjust the height of the chair. (This was done in order to bring the subject's interaural axis into line with the 0^{o} elevation position on the mast.) As you have probably noticed, there are 12 lines radiating out from the centre of your chair. The middle of each of the lines has a number where the sound you will be localizing could come. That rack of equipment generates and controls the sound, and this pole with its attached speaker allows me to present the sound to you from any one of these 12 numbered positions. (At this point the experimenter demonstrated the operation of the pole by placing it at azimuth 1 and then returning it to position 12 again.) I'd like you to think of yourself as seated at the centre of a large clock, its numbers representing the 12 sound sources marked on the floor. Your task during the experiment will be to tell me while you are blindfolded from which one of these 12 positions you hear the sound coming. Don't be surprised if this sound appears to come from a different position each time I present it, the same position more than once, or one position all the time. I'll keep track of your scores during the experiment and give you your results at the end.

The subject was then assured that no one else would be told how he or she performed on the task, and the subject was then given a few minutes to familiarize him or herself with the positions of the 12 lines.

When the subject felt confident he or she could mentally visualize the lines, the experimenter then initiated the training/no-training manipulations. For the training condition the instructions opened as follows:

> The experiment is divided into a number of parts. During the first part if you correctly identify the location of the sound when it is presented, I'll say correct; if you incorrectly identify it, I'll say incorrect and then tell you the number of the correct direction.

For the no-training condition the opening sentence of the instructions was identical to the above, followed by:

> During the first part, I will not tell you whether your choice of the sound direction is correct or incorrect; I'll simply go on to the next sound presentation.

The remainder of the instructions were identical for both conditions:

> Please don't give your answer until the sound has stopped. You will only be allowed one answer so be sure of your choice before telling me. Also, you must reply using only one number--for example, you can't report that the sound appears to be between say 1 and 2, you must choose either position 1 or 2. So that you'll know when to expect the sound, a background noise which I'll turn on for you in a moment will go off a few seconds before I present the sound you are to localize. This background noise will then be turned on again after you have made your choice and I've told you whether you were right or wrong, and if wrong, the correct number (the last

clause of this sentence was omitted for the no-training condition).

The experimenter also informed the subject that the background noise would always be on the same length of time and that this noise helped to cover up any noises he might make while moving around the room. The experimenter then turned the background noise on for two seconds.

At this point the subject was told that the loudness of the sound to be localized would now be adjusted, and he or she was given instructions how this would be accomplished. Before this procedure was initiated, the subject was informed whether he or she would be a monaural, a possibility mentioned during recruitment. The subject was then fitted with a pair of Accu-Fit™ ear plugs, the headband was tightened comfortably around his or her head, and the modified MSA muffs were placed over his or her ears. The subject was then blindfolded, and the experimenter insured he or she was facing azimuth 12. The localization signal was then turned on, with the speaker mast at either 270° or 90° azimuth opposite the ear randomly chosen to remain occluded for the monaural subject or opposite a randomly chosen ear for the binaural. Using the method of ascending and descending limits, the experimenter manipulated the signal level with the attenuator until a value was consistently obtained where the subject indicated he or she could not hear the signal (i.e, RL was reached). When absolute threshold was obtained, the signal was attenuated an additional 5 dB SPL, and this level was used for all testing. Next, the blindfold was removed, and for the monaural subject, the muff and ear plug were removed from the ear opposite the one designated to remain occluded; for the binaural both muffs and plugs were removed.

At this point the experimenter performed the head fixed and head rotate manipulations. For the head fixed condition the instructions were as follows:

> Your head will be kept facing straight forward by my connecting the two rods on your headband to this stabilizer yoke attached to the backrest. The purpose of this arrangement is to eliminate any involuntary head movements. After I've joined the yoke to the band, I'd like you to keep your head as still as possible; that is, try not to turn it inside the band. Also, try to keep the rest of your body stationary during the presentation of the sound because even slight movements of your arms and legs could adversely affect the experimental results.

The subject was also informed that he or she could readily slip out of the headband if for any reason he or she felt upset (none did) and that at the end of Part II of the experiment the headband would be released from the yoke. For the head rotate condition the instructions were as follows:

> The instant you hear the sound you are to localize, I'd like you to move your head horizontally a comfortable distance toward the position from which you perceive the sound to come. Regardless of where the localization sound appears to be--in front, behind, left or right--it is very important that you move your head during every presentation of the sound. I'll demonstrate how far you should turn your head now. (The experimenter turned his head 10^{o} to 15^{o} to the left and right and had the subject

do the same, correcting him or her if necessary.) You may rotate your head during the sound as often as you feel it necessary to be confident of your choice, but make sure you rotate to the left or right only, not up or down. While rotating your head, try to keep the rest of your body stationary because even slight movements of your arms and legs could adversely affect the experimental results.

After the head fixed or head rotate instructions were given, the experimenter briefly recapitulated the appropriate instructions for the subject. He then readied the subject (e.g., connected the headband to the yoke) for the 12 trials of Phase I and then placed the blindfold over the subject's eyes.

The experimenter then initiated the background noise and positioned the speaker mast at the required position. The background noise remained on for 27 seconds and was immediately followed by 2 seconds of silence, after which the localization stimulus sounded for 2 seconds. The subject then reported his or her choice, this was recorded, feed-back was given, if required, and the next trial was initiated--and so on.

At the end of the 12 trials, Phase II commenced, and the experimenter gave the following instructions to subjects in the training condition:

We are now starting Part II, and for this part I'll not tell you whether your choice is correct or not. Simply give your answer as before, but don't expect any comments. There are no other changes in the routine.

Subjects in the no-training condition were told to continue as they had been doing.

At the completion of Phase II, Phase III began, and the necessary changes in the apparatus were made. Subjects in the head rotate and head fixed conditions were switched to the head fixed and head rotate conditions, respectively, and given the appropriate instructions. Subjects in the training condition were told they would receive feedback again; the no-training condition subjects were requested to continue responding just as they had been doing. The instructions appropriate to the subject's condition were then recapitulated as in Phase I.

For Phase IV, subjects in the training condition were again told they would no longer receive feedback and those in the no-training condition were asked to continue responding as usual.

At the end of Phase IV, the experimenter helped the subject out of the apparatus and then debriefed him or her. One question always asked of the subject was the following:

> Did you at any time believe that you could identify the source positions from any cues other than the sounds themselves? For example, did you try to make your position estimate on the basis of where I was as I walked around you and moved the speaker pole?

Only rarely did a subject report hearing the experimenter move during the time the background noise was on, and on these occasions his movements were of no help to the subject in determining the direction of the sound.

Following the debriefing, the subjects were thanked for their participation, and told the results of the experiment would be posted outside the test room at a later date. Before leaving, they were asked not to discuss the experiment with other students.

Chapter III

Results

Preliminary Analysis

To determine if the two monaural groups (left and right ear occluded) could be combined, the errors for the monaural left group were reflected, i.e., scored as if the right ear had been plugged, and the error scores in degrees for the reflected and monaural right groups were submitted to a 2 x 12 (reflected versus right monaural x azimuth) analysis of variance (see Table 1). As the main effect of the side of monaurality and the interaction were nonsignificant, the groups were combined; the following analyses are based on the reflected data, with all monaurals being considered as right ear occluded.

For organizational purposes, the rest of the results will be presented under the following headings: (a) Overview of the major findings, (b) Interaction Analyses, and (c) Hypotheses Testing.

Overview

The major findings are shown in Figures 4, 5, and 6, along with Table 2 (when referring to these figures, note that the numbers representing azimuth are the clock face positions used by the subjects for reporting stimulus location):

1. Binaural listeners free to rotate their heads had the smallest error scores, and these scores were independent of azimuth (see Figure 4).

2. For binaural listeners, fixing the head produced a considerable increase in the size of errors in the rear quadrant, but not elsewhere.

Table 1

Analysis of Variance of Error Scores
for Left and Right Ear Monaurals

Source	SS	df	MS	F
Between subjects	107,805.73	35		
Monaural ear (M)	792.19	1	792.19	0.25
Subject w. groups	107,013.54	34	3,147.46	
Within subjects	618,918.75	396		
Azimuth (A)	175,930.73	11	15,993.70	13.71*
M x A	6,639.06	11	603.55	0.52
A x subj. w. groups	436,348.96	374	1,166.71	

*p < .001.

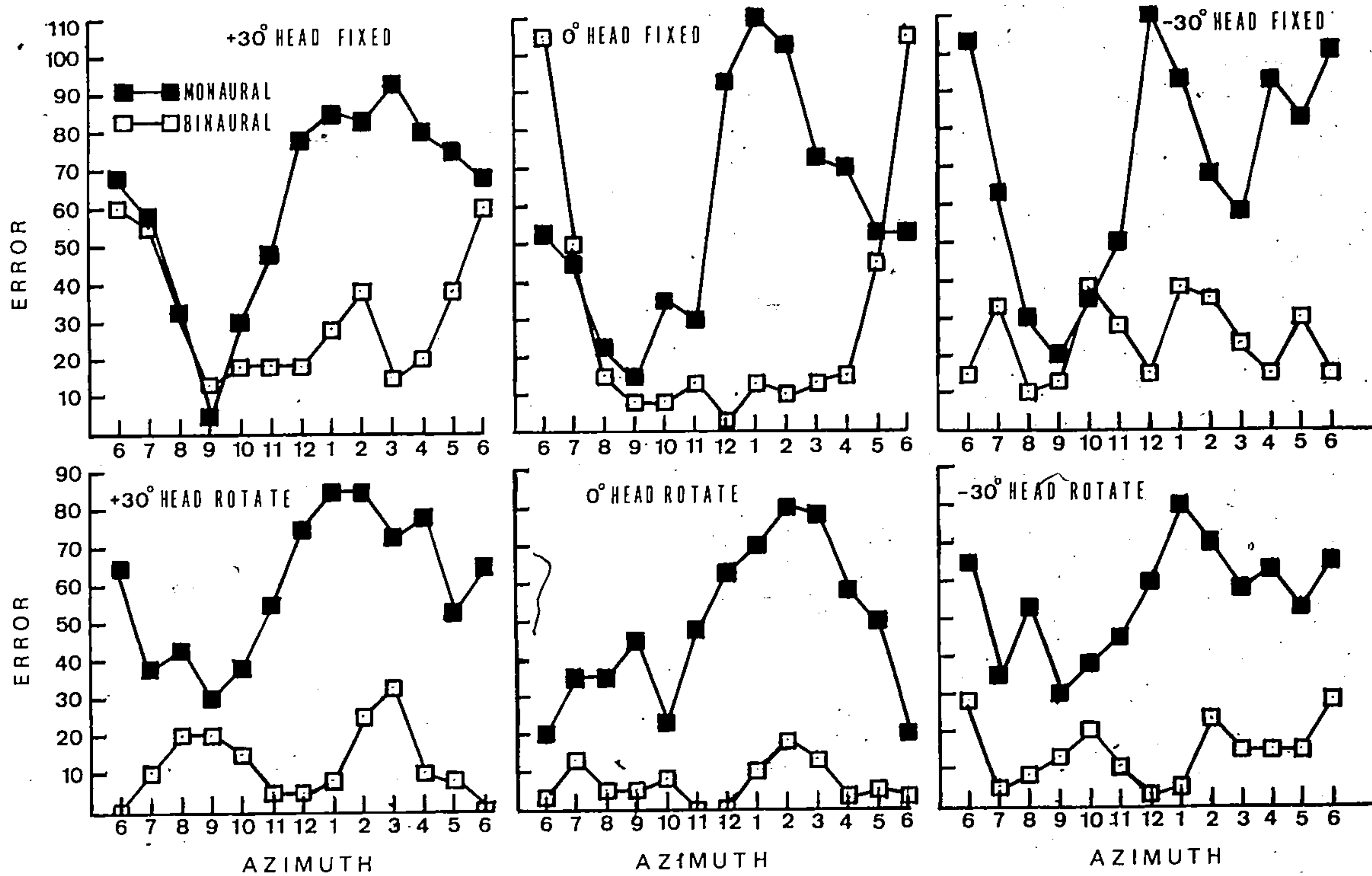

Figure 4. Mean error in degrees as a function of azimuth (clock-code), hearing condition, elevation, and head movement. (For all figures in this report, Azimuth 9 represents the side facing the monaurals' non-occluded ear.)

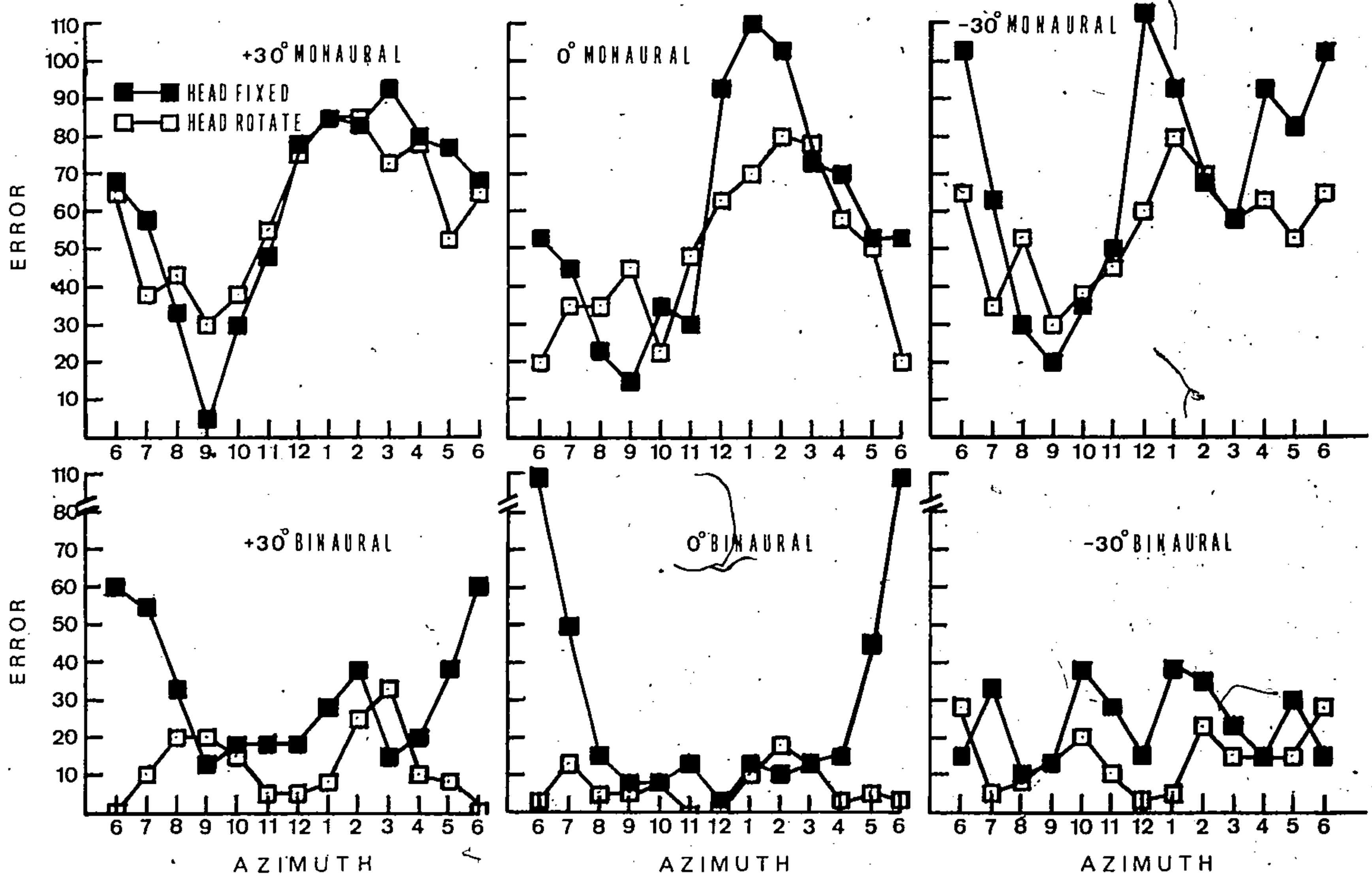

Figure 5. Mean error in degrees as a function of azimuth (clock-code), head movement, elevation and hearing condition.

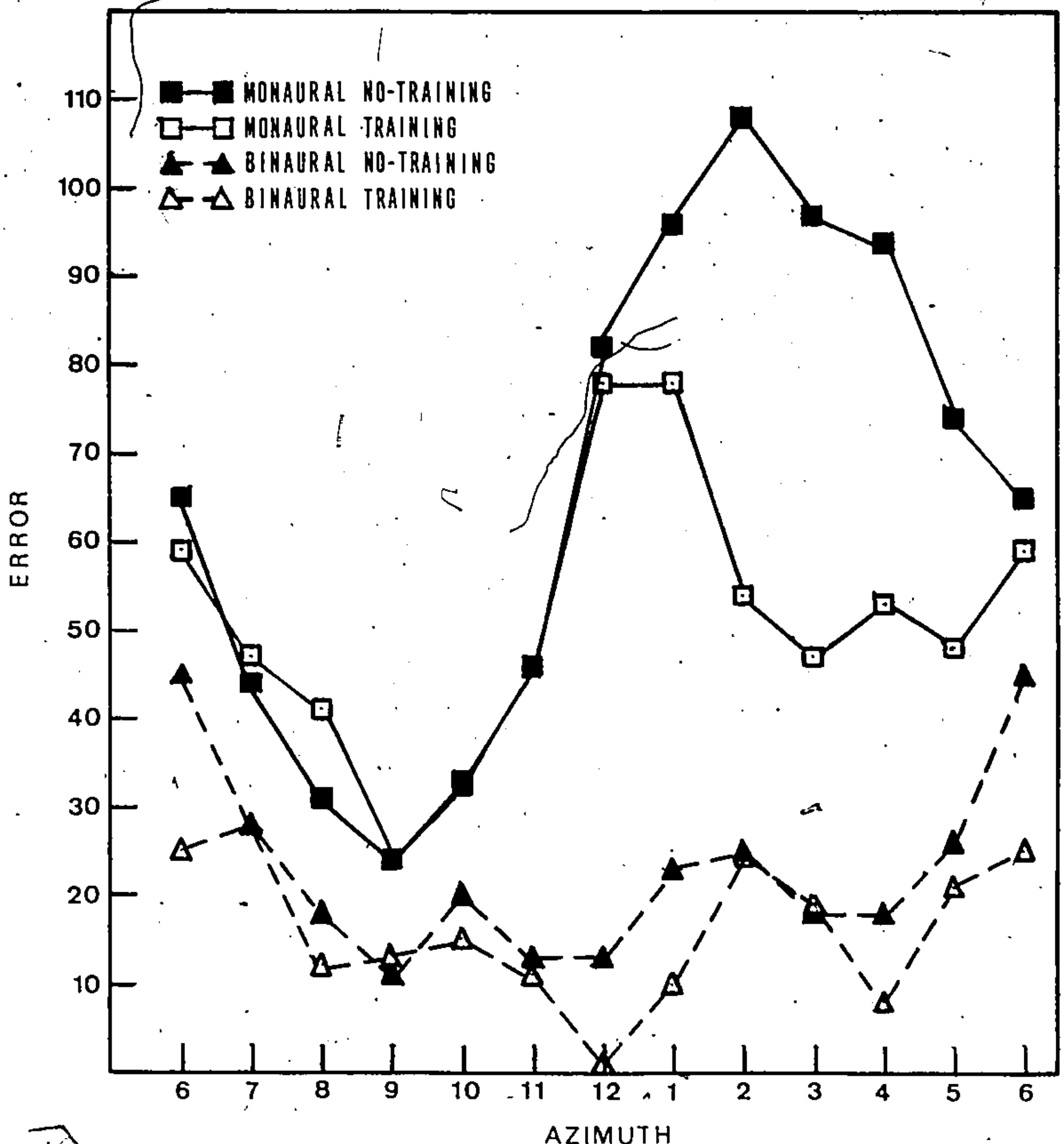

Figure 6. Mean error in degrees as a function of azimuth (clock-code), hearing condition, and training.

Table 2

Analysis of Variance of Error Scores

Source	SS	df	MS	F[a]
Between subjects				
Hearing condition (H)	687,604.69	1	687,604.69	215.01***
Elevation (E)	10,794.79	2	5,397.40	1.69
Training (T)	50,375.52	1	50,375.52	15.75***
H x E	865.62	2	432.81	0.14
H x T	10,063.02	1	10,063.02	3.15
E x T	24,113.54	2	12,056.77	3.77*
H x E x T	4,701.04	2	2,350.52	0.73
Subj. w. groups	191,881.25	60	3,198.02	
Within subjects				
Head movement (M)	55,013.02	1	55,013.02	25.95***
M x H	5,963.02	1	5,963.02	2.81
M x E	1,451.04	2	725.52	0.34
M x T	325.52	1	325.52	0.15
M x H x E	5,301.04	2	2,650.52	1.25
M x H x T	5,313.02	1	5,313.02	2.51
M x E x T	2,232.29	2	1,116.15	0.53
M x H x E x T	2,357.29	2	1,178.65	0.56
M x subj. w. groups	127,206.25	60	2,120.10	
Azimuth (A)	209,680.73	11	19,061.88	12.71***
A x H	191,114.06	11	17,374.01	11.59***
A x E	17,292.71	22	786.03	0.52
A x T	47,518.23	11	4,319.84	(2.88)**
A x H x E	67,721.87	22	3,078.27	(2.05)**
A x H x T	58,805.73	11	5,345.98	(3.56)***
A x E x T	27,073.96	22	1,230.63	0.82
A x H x E x T	33,586.46	22	1,526.66	1.02
A x subj. w. groups	989,743.75	660	1,499.61	
M x A	78,480.73	11	7,134.61	7.12***
M x A x H	20,855.73	11	1,895.98	(1.89)*
M x A x E	27,261.46	22	1,239.16	1.24
M x A x T	7,518.23	11	683.48	0.68
M x A x H x E	50,211.46	22	2,282.34	(2.28)***
M x A x H x T	11,605.73	11	1,055.07	1.05
M x A x E x T	22,980.21	22	1,044.55	1.04
M x A x H x E x T	18,655.21	22	847.96	0.85
MA x subj. w. groups	661,118.75	660	1,001.70	

[a]Values in brackets indicate the *F* was significant by the conventional *F* test but nonsignificant by the conservative.

$^{*}p < .05$.

$^{**}p < .01$.

$^{***}p < .001$.

And this trend was influenced by elevation (see Figure 4). No similar rear quadrant error size increase was noted for monaurals.

3. Localization accuracy for monaurals and binaurals was not always improved with head rotation. In fact, at some azimuths, for example opposite the non-occluded ear for monaurals and in the frontal region for binaurals, accuracy decreased for the head rotate condition (see Figure 5).

4. As Figure 6 shows, training monaural listeners increased their accuracy on the occluded ear side, but had a nonsignificant influence at the remaining azimuths. For binaurals, however, training made no significant improvement in accuracy in any quadrant.

5. On their occluded side, untrained or head fixed monaural listeners were clearly inferior to binaurals (see Figures 6 and 4); however, on their non-occluded side their performance often matched binaural.

Interaction Analyses

To explore the interactive effects of the four variables (azimuthal angle, elevation, training, and head movement) on monaural versus binaural accuracy, the error scores in degrees for Phases II and IV were analyzed using a 2 x 2 x 3 x 2 x 12 analysis of variance (see Appendix A for the complete summary table). The error variances pooled to create the mean square subjects within groups error term were homogeneous, F max obtained = 10.76, ns, but the symmetries of the pooled 12 x 12 and 24 x 24 dispersion matrices did not have the required form (compound symmetry test for the BMDP2V ANOVA programme). Accordingly, conservative F tests were conducted, and those treatment effects which were significant beyond the .05 level by the conventional

F test but nonsignificant by the conservative test are indicated in the Table 2 ANOVA summary (page 98). The remaining significant results were significant using either test. (It should be noted that the BMDP2V test for compound symmetry is likely to show significance for large sample sizes; violation of the symmetry assumption, however, may have a negligible effect on the analysis of variance. Based on this consideration, I chose to interpret the results of the conventional *F* tests.)

The approach to be taken in discussing the results shown in Table 2 will be to analyze each interaction hierarchy associated with a main effect, beginning first with the between variables. To eliminate the constant repetition of statements concerning nonsignificant results, only those tests of simple effects which were significant will be reported.

Although the main effect of elevation was nonsignificant, the error scores were smaller at 0° (M = 34.94) than at the remaining two elevations, both of which had almost identical means ($+30^{\circ}$ = 40.72, -30° = 39.58). The significant main effect of training, indicating that subjects who received training had smaller error scores (M = 33.02) than those who did not (M = 43.81), was modified by the significant Elevation x Training interaction illustrated in Figure 7. Analysis of simple main effects (see Table 3) revealed that the error scores for subjects receiving training were significantly smaller only at $+30^{\circ}$.

The main effect of training was also qualified by the significant Azimuth x Training interaction (see Figure 8). As Table 4 shows, trained subjects were significantly more accurate than untrained at

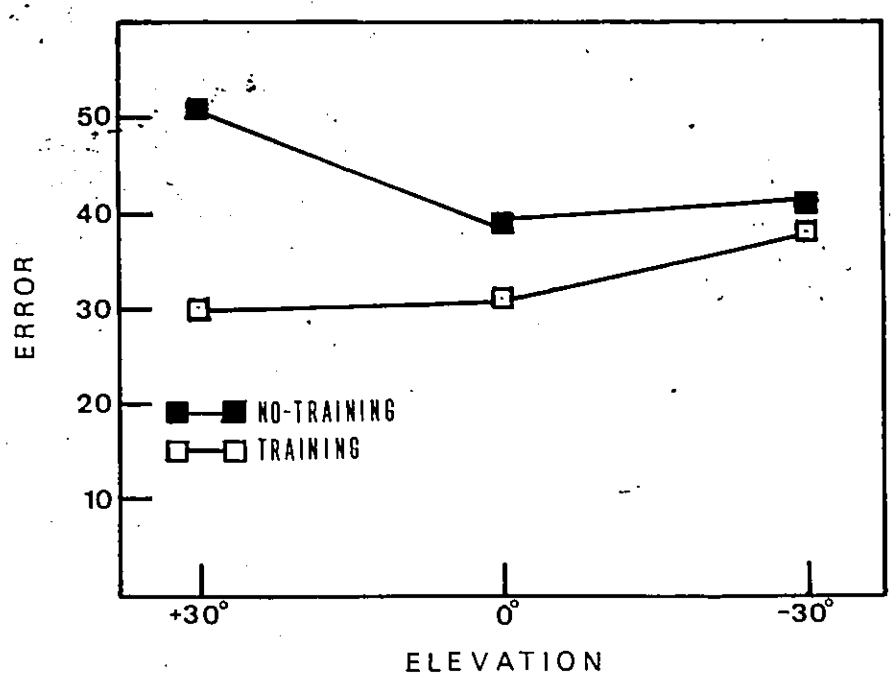

Figure 7. Mean error in degrees as a function of elevation and training.

Table 3

Analysis of Variance for Simple Effects of Training for the Elevation x Training Interaction

Source	SS	df	MS	F
Between subjects				
Between T at $+30^{\circ}$	62,500.00	1	62,500.00	19.54*
0°	10,764.06	1	10,764.06	3.37
-30°	1,225.00	1	1,225.00	0.38
Subj. w. groups	191,881.25	60	3,198.02	

Note. T = training variable; +30, 0, and -30° = levels of elevation.

$^{*}p < .01$.

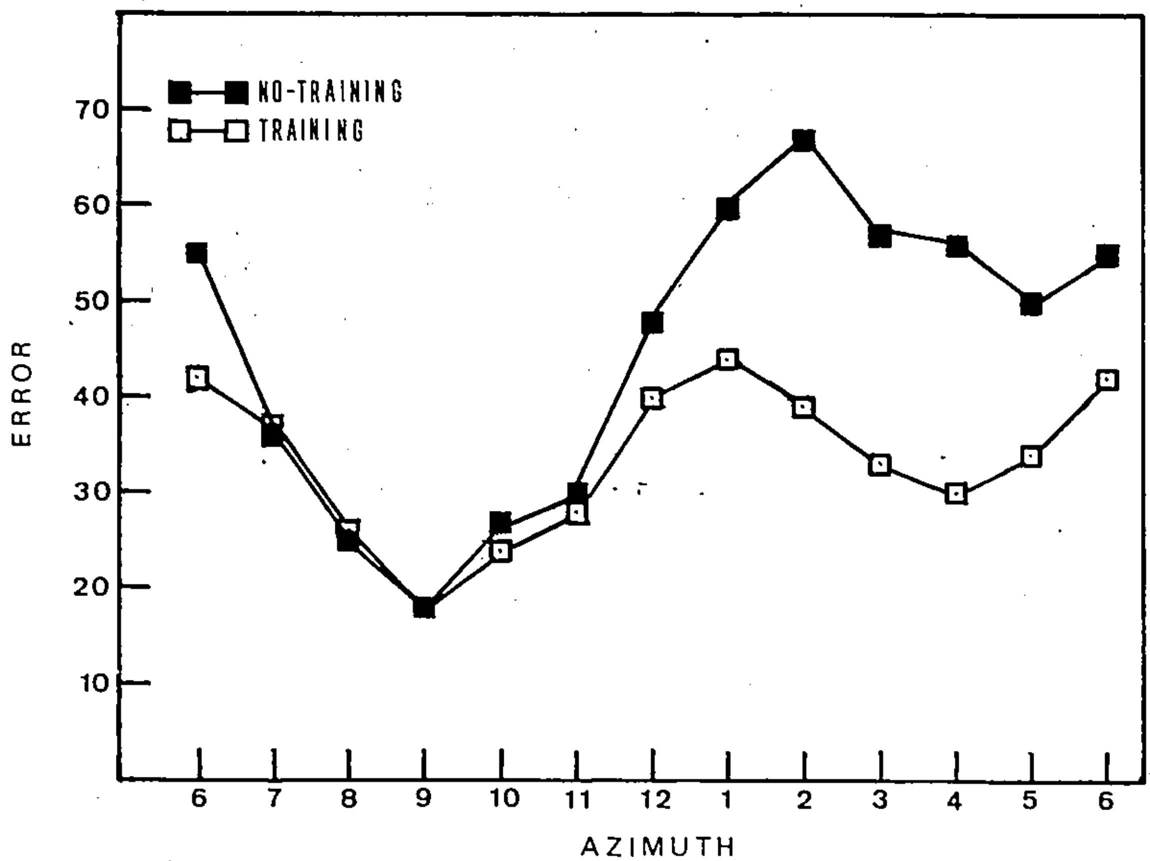

Figure 8. Mean error in degrees as a function of azimuth (clock-code) and training.

Table 4

Analysis of Variance for Simple Effects of Training for the Azimuth x Training Interaction

Source	*SS*	*df*	*MS*	*F*
Between subjects				
Between T at A_1	8,556.25	1	8,556.25	5.21*
A_2	27,225.00	1	27,225.00	16.59**
A_3	21,025.00	1	21,025.00	12.81**
A_4	23,256.25	1	23,256.25	14.17**
A_5	9,025.00	1	9,025.00	5.50*
A_6	6,006.25	1	6,006.25	3.66
A_7	56.25	1	56.25	0.03
A_8	100.00	1	100.00	0.06
A_9	25.00	1	25.00	0.02
A_{10}	306.25	1	306.25	0.19
A_{11}	56.25	1	56.25	0.03
A_{12}	2,256.25	1	2,256.25	1.37
Subj. w. groups + A x subj. w. groups	1,181,625.00	720	1,641.15	

Note. T = training variable; A_1 to A_{12} = azimuth level.

*$p < .05$.

**$p < .01$.

azimuths 1 to 5. The first-order interaction was further qualified by the significant second-order interaction, Azimuth x Hearing Condition x Training illustrated in Figure 6 (page 97). The simple Azimuth x Training interaction at the binaural level was nonsignificant, F (11,660) = .54, ns, indicating that binaurals who received training did not perform better than those who did not. At the monaural level, however, the effects of training were more varied as indicated by the significant simple Azimuth x Training interaction, F (11,660) = 5.90, $p < .01$. Furthermore, simple simple main effects tests revealed (see Table 5) that monaurals who received training had significantly smaller error scores than untrained monaurals at azimuths 2, 3, 4, and 5.

As Table 2 shows there was a significant main effect of hearing condition, with monaurals being less accurate (M = 58.36) than binaurals (M = 18.47). But this effect was modified by the significant Azimuth x Hearing Condition interaction depicted in Figure 9. Breakdown of the interaction showed (see Table 6) that the binaurals performed significantly better than monaurals at all azimuths except azimuth 9 (A9). This interaction was in turn qualified by the significant Azimuth x Hearing Condition x Training interaction illustrated by the second profile pattern (i.e., monaurals versus binaurals at each azimuth for each of the two training levels) present in Figure 6, page 97. The simple Hearing Condition x Azimuth interaction for subjects receiving training (T_1) was significant, F (11,660) = 4.67, $p < .01$, with the simple simple main effects tests (see Table 7) revealing that binaurals localized more accurately at all azimuths except A9 and 10. For the no-training condition (T_2), the simple interaction was significant,

Table 5

Analysis of Variance for Simple Simple Effects of Training at the Monaural Level for the Simple Azimuth x Training Interaction

Source	SS	df	MS	F
Between subjects				
Between T at A_1	5,512.50	1	5,512.50	3.36
A_2	52,812.50	1	52,812.50	32.18*
A_3	45,000.00	1	45,000.00	27.42*
A_4	31,250.00	1	31,250.00	19.04*
A_5	12,800.00	1	12,800.00	7.80*
A_6	612.50	1	612.50	0.37
A_7	112.50	1	112.50	0.07
A_8	1,800.00	1	1,800.00	1.10
A_9	0.00	1	0.00	0.00
A_{10}	12.50	1	12.50	0.01
A_{11}	0.00	1	0.00	0.00
A_{12}	200.00	1	200.00	0.12
Subj. w. groups + A x subj. w. groups	1,181,625.00	720	1,641.15	

Note. T = training variable; A_1 to A_{12} = azimuth level.

*$p < .01$.

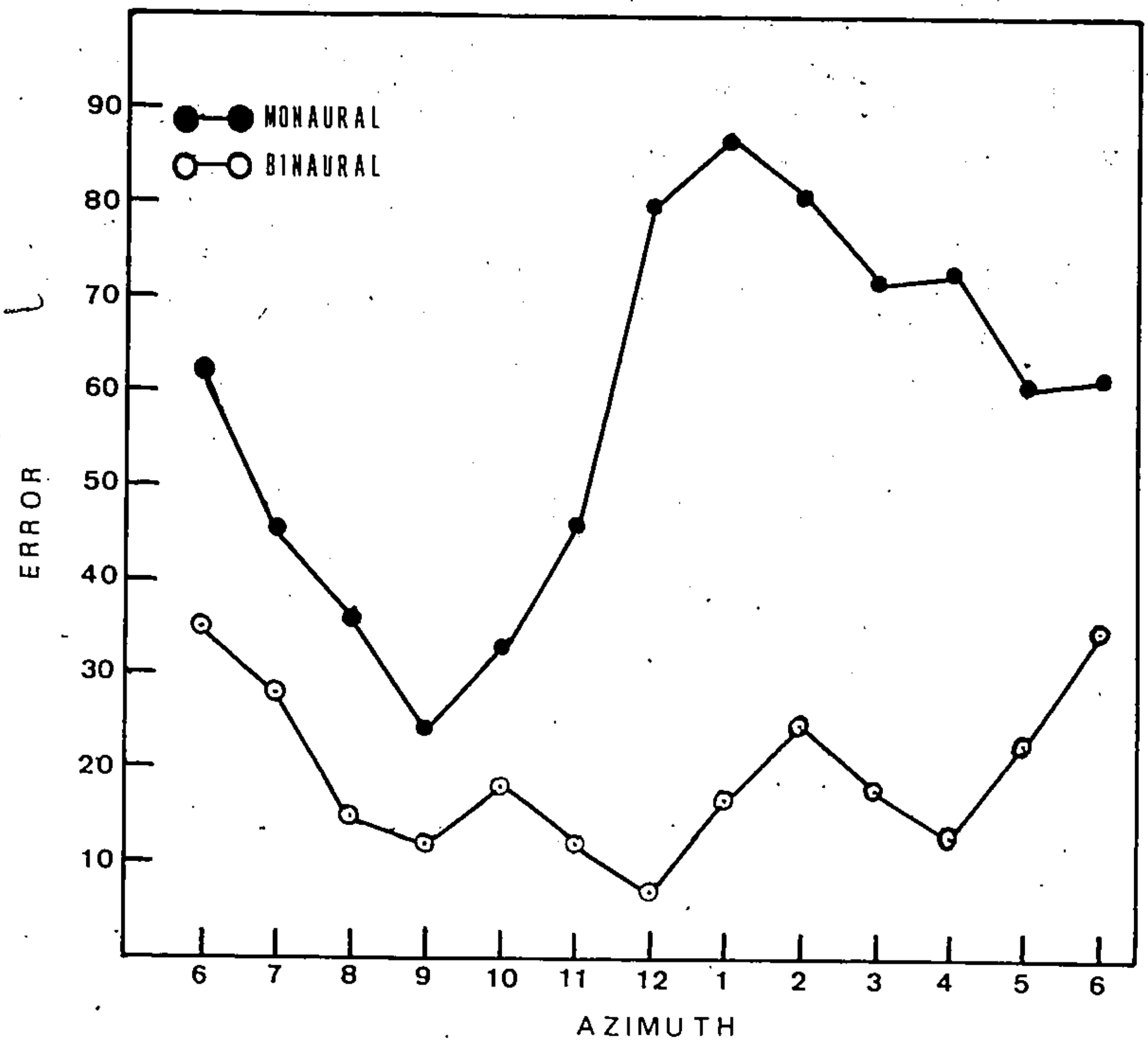

Figure 9. Mean error in degrees as a function of azimuth (clock-code) and hearing condition.

Table 6

Analysis of Variance for Simple Effects of Hearing Condition for the Azimuth X Hearing Condition Interaction

Source	SS	df	MS	F
Between subjects				
Between H at A_1	178,506.25	1	178,506.25	108.77**
A_2	115,600.00	1	115,600.00	70.44**
A_3	102,400.00	1	102,400.00	62.40**
A_4	131,406.25	1	131,406.25	80.07**
A_5	50,625.00	1	50,625.00	30.85**
A_6	26,406.25	1	26,406.25	16.09**
A_7	11,556.25	1	11,556.25	7.04**
A_8	15,625.00	1	15,625.00	9.52**
A_9	5,625.00	1	5,625.00	3.43
A_{10}	8,556.25	1	8,556.25	5.21*
A_{11}	41,006.25	1	41,006.25	24.99**
A_{12}	191,406.25	1	191,406.25	116.63**
Subj. w. groups + A x subj. w. groups	1,181,625.00	720	1,641.15	

Note. H = hearing condition; A_1 to A_{12} = azimuth level.

*$p < .05$.

**$p < .01$.

Table 7

Analysis of Variance for Simple Simple Effects of Hearing Condition for the Azimuth x Hearing Condition x Training Interaction

Source	SS	df	MS	F
Between subjects				
Between H at T_1A_1	84,050.00	1	84,050.00	51.21**
A_2	16,200.00	1	16,200.00	9.87**
A_3	13,612.50	1	13,612.50	8.29**
A_4	35,112.50	1	35,112.50	21.40**
A_5	12,800.00	1	12,800.00	7.80**
A_6	21,012.50	1	21,012.50	12.80**
A_7	6,612.50	1	6,612.50	4.03*
A_8	15,312.50	1	15,312.50	9.33**
A_9	2,450.00	1	2,450.00	1.49
A_{10}	5,512.50	1	5,512.50	3.36
A_{11}	22,050.00	1	22,050.00	13.44**
A_{12}	108,112.50	1	108,112.50	65.88**
Between H at T_2A_1	94,612.50	1	94,612.50	57.65**
A_2	125,000.00	1	125,000.00	76.17**
A_3	112,812.50	1	112,812.50	68.74**
A_4	105,800.00	1	105,800.00	64.47**
A_5	42,050.00	1	42,050.00	25.62**
A_6	7,200.00	1	7,200.00	4.39*
A_7	5,000.00	1	5,000.00	3.05
A_8	2,812.50	1	2,812.50	1.71
A_9	3,200.00	1	3,200.00	1.95
A_{10}	3,200.00	1	3,200.00	1.95
A_{11}	19,012.50	1	19,012.50	11.58**
A_{12}	84,050.00	1	84,050.00	51.21**
Subj. w. groups + A x subj. w. groups	1,181,625.00	720	1,641.15	

Note. H = hearing condition; T_1 = training, T_2 = no-training; A_1 to A_{12} = azimuth level.

*$p < .05$.

**$p < .01$.

$\underline{F}$ (11,660) = 10.47, $\underline{p} < .01$; tests of simple effects outlined in the bottom half of Table 7 showed that monaurals performed no differently from the binaurals at A7, 8, 9, and 10, but significantly poorer at the remaining azimuths. To summarize, for both the training and no-training conditions, monaurals were inferior to binaurals at azimuths A1 to 6 and 11 and 12. At azimuths A7 to 10 there was no difference in the performance of the two groups for the no-training condition; however, for the training condition binaurals were superior at A7 and 8 but not so at A9 and 10.

The effects of the Azimuth x Hearing Condition interaction were also significantly modified over elevations (Azimuth x Hearing Condition x Elevation interaction) and levels of head movement (Head Movement x Azimuth x Hearing Condition), with both these second-order interactions being further significantly influenced by the Head Movement x Azimuth x Hearing Condition x Elevation interaction.

Considering first the Azimuth x Hearing Condition x Elevation interaction, illustrated in Figure 10, for each elevation the simple interaction was significant: $+30^{\circ}$, $\underline{F}$ (11,660) = 4.30, $\underline{p} < .01$; 0°, $\underline{F}$ (11,660) = 7.65, $\underline{p} < .01$; -30°, $\underline{F}$ (11,660) = 3.72, $\underline{p} < .01$. As Table 8 shows at $+30^{\circ}$ elevation the binaurals had significantly smaller error scores than the monaurals at all azimuths except A7, to A10, inclusive. At azimuths 6, 7, 8, and 10, and A9 and 10 for elevations 0° and -30°, respectively, there was no significant difference between the monaurals and binaurals. Examining this second-order interaction in more detail by means of the Head Movement x Azimuth x Hearing Condition x Elevation interaction graphed in Figure 4 (page 95) indicates there is a trend across elevations for monaural

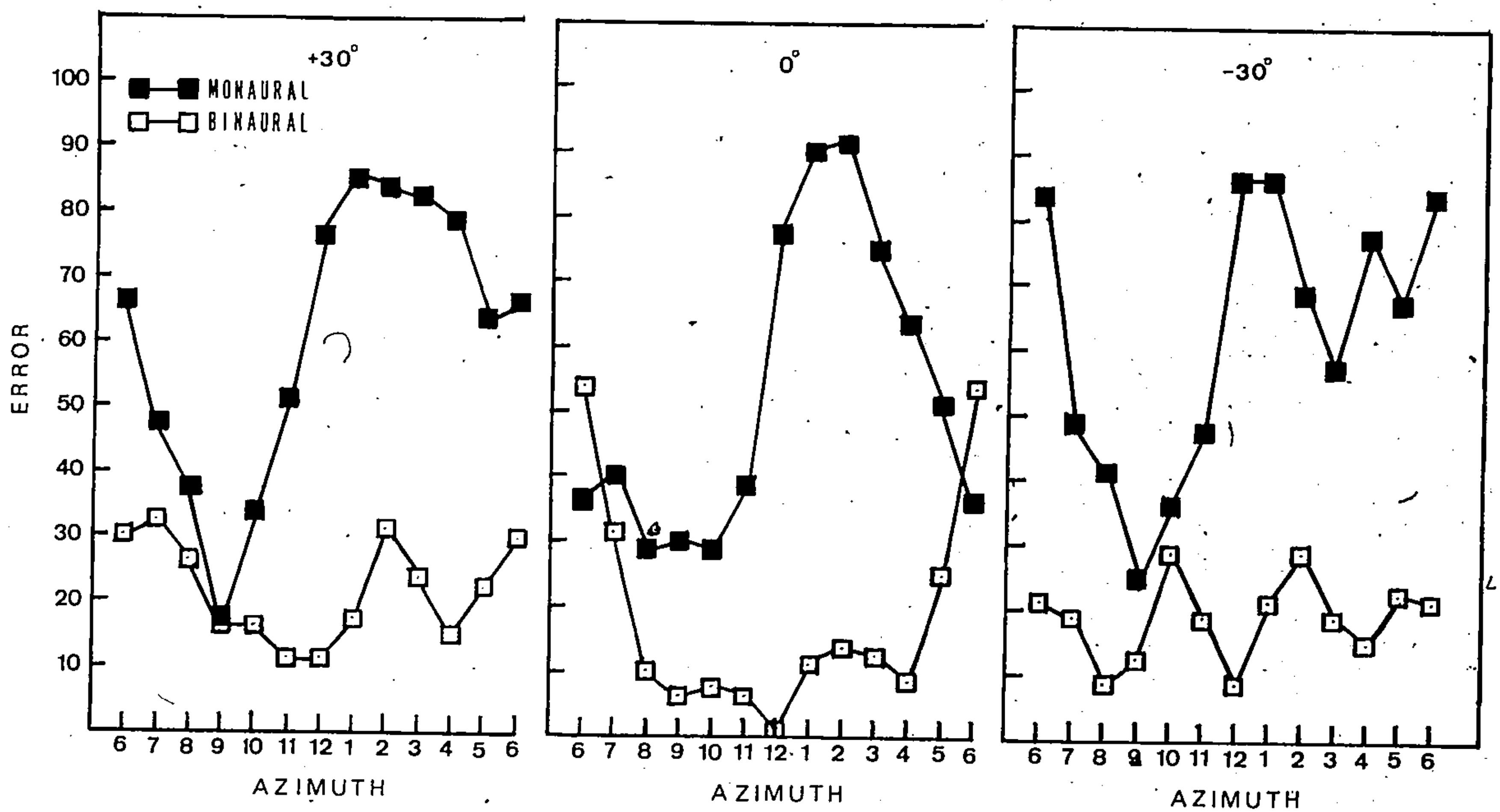

Figure 10. Mean error in degrees as a function of azimuth (clock-code), hearing condition, and elevation.

Table 8

Analysis of Variance for Simple Simple Effects of Hearing Condition for the Azimuth x Hearing Condition x Elevation Interaction

Source	SS	df	MS	F
Between subjects				
Between H at E_1A_1	54,675.00	1	54,675.00	33.32**
A_2	33,075.00	1	33,075.00	20.15**
A_3	41,418.75	1	41,418.75	25.24**
A_4	48,768.75	1	48,768.75	29.72**
A_5	20,418.75	1	20,418.75	12.44**
A_6	15,768.75	1	15,768.75	9.61**
A_7	2,700.00	1	2,700.00	1.65
A_8	1,518.75	1	1,518.75	0.93
A_9	18.75	1	18.75	0.01
A_{10}	3,675.00	1	3,675.00	2.24
A_{11}	19,200.00	1	19,200.00	11.70**
A_{12}	50,700.00	1	50,700.00	30.89**
Between H at E_2A_1	74,418.75	1	74,418.75	45.35**
A_2	72,075.00	1	72,075.00	43.92**
A_3	46,875.00	1	46,875.00	28.56**
A_4	36,300.00	1	36,300.00	22.12**
A_5	8,268.75	1	8,268.75	5.04*
A_6	3,675.00	1	3,675.00	2.24
A_7	918.75	1	918.75	0.56
A_8	4,218.75	1	4,218.75	2.57
A_9	6,768.75	1	6,768.75	4.12*
A_{10}	5,418.75	1	5,418.75	3.30
A_{11}	12,675.00	1	12,675.00	7.72**
A_{12}	69,768.75	1	69,768.75	42.51**

Table 8-(Continued)

Source	SS	df	MS	F
Between H at E_3A_1	50,700.00	1	50,700.00	30.89**
A_2	19,200.00	1	19,200.00	11.70**
A_3	18,018.75	1	18,018.75	10.98**
A_4	46,875.00	1	46,875.00	28.56**
A_5	24,300.00	1	24,300.00	14.81**
A_6	46,875.00	1	46,875.00	28.56**
A_7	10,800.00	1	10,800.00	6.58*
A_8	12,675.00	1	12,675.00	7.72**
A_9	1,875.00	1	1,875.00	1.14
A_{10}	675.00	1	675.00	0.41
A_{11}	9,918.75	1	9,918.75	6.04*
A_{12}	72,075.00	1	72,075.00	43.92**
Subj. w. groups + A x subj. w. groups	1,181,625.00	720	1,641.15	

Note. H = hearing condition; E_1 to E_3 = elevations +30, 0, and -30°, respectively; A_1 to A_{12} = azimuth level.

*$p < .05$.

**$p < .01$.

performance to be inferior to binaural at azimuths 11 through 5 for both the head fixed and head rotate conditions. However, at elevations +30° and 0° for the head fixed condition, monaural performance at azimuths 6 to 9 was as good as binaural, if not better (note the reversal for binaurals at A6). Whereas, for the head rotate condition, binaurals were more accurate than monaurals at these same azimuths. At −30° elevation, monaural performance for the head fixed condition was as accurate as binaural only at azimuth A10; for the head rotate condition the binaurals were superior at all azimuths.[1]

The change in the Azimuth x Hearing Condition interaction effects over head movement levels (i.e., Head Movement x Azimuth x Hearing Condition interaction) is shown in Figure 11. At the head fixed level, the simple interaction was significant, $\underline{F}\ (11, 1320) = 11.46$, $\underline{p} < .01$, with monaurals and binaurals performing equally well at A6, 7, 8, 9, and 10, but with binaurals having significantly lower error scores at the remaining azimuths (see Table 9). The simple Hearing Condition x Azimuth interaction was also significant at the head rotate level, $\underline{F}\ (11, 1320) = 3.94$, $\underline{p} < .01$; tests of simple simple main effects revealed the binaurals were significantly more accurate than monaurals at all azimuths. However, as noted earlier, the elevation of the source had a significant effect on this three-way interaction. Returning again to Figure 4 (page 95), but with emphasis now on elevation, for elevations +30° and 0°, monaurals were less accurate than binaurals at azimuths 1 to 5 and 10 to 12. For −30°, however, monaurals were inferior at azimuths 1 to 9 and 11 to 12. At +30° and 0° under the head fixed condition, the two groups either performed equally well at azimuths 6 to 9, or else the monaurals were more

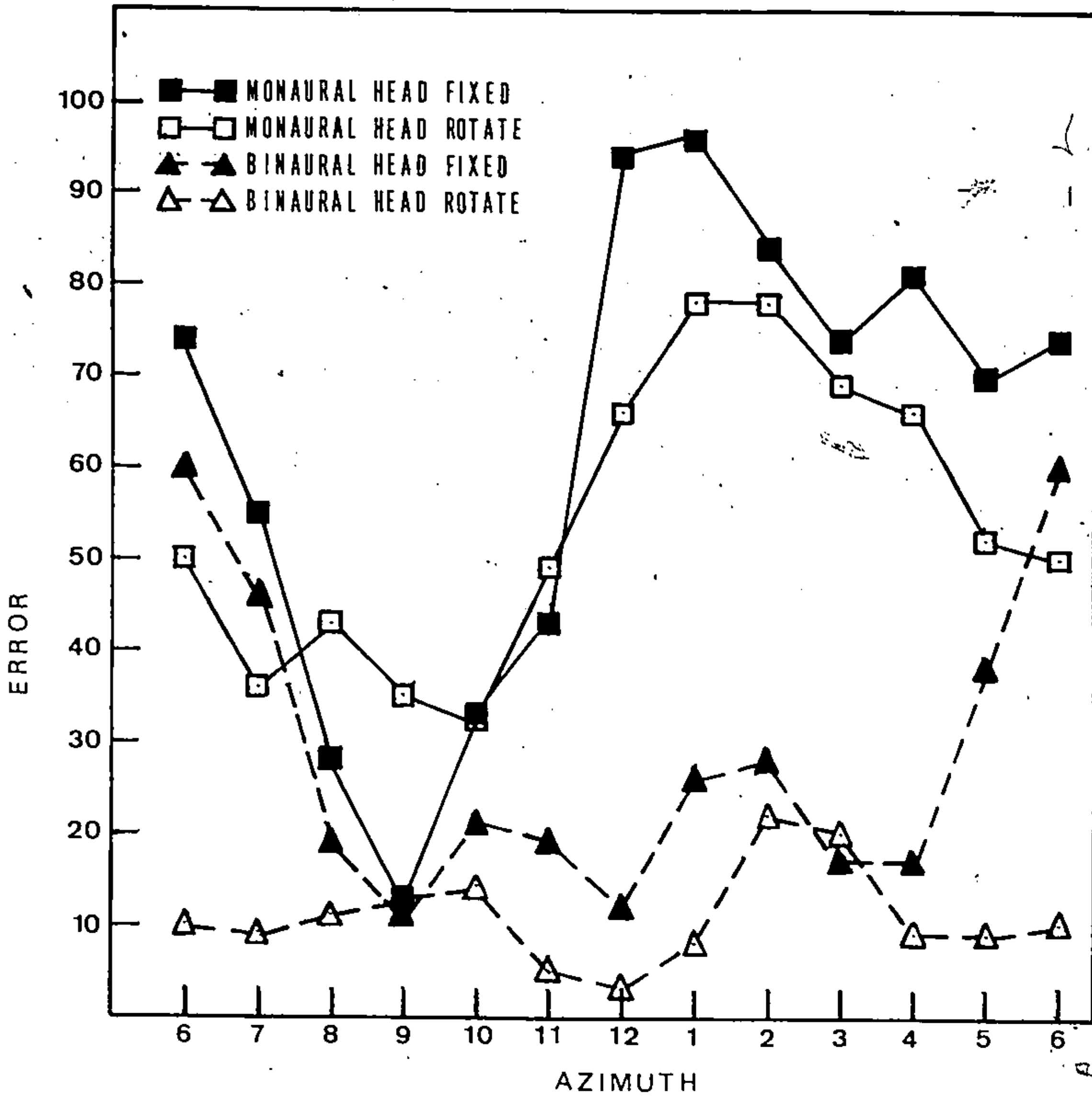

Figure 11. Mean error in degrees as a function of azimuth (clock-code), hearing condition, and head movement.

Table 9

Analysis of Variance for Simple Simple Effects of Hearing Condition for the Head Movement x Azimuth x Hearing Condition Interaction

Source	SS	df	MS	F
Between subjects				
Between H at M_1A_1	88,200.00	1	88,200.00	64.47**
A_2	57,800.00	1	57,800.00	42.25**
A_3	59,512.50	1	59,512.50	43.50**
A_4	74,112.50	1	74,112.50	54.17**
A_5	19,012.50	1	19,012.50	13.90**
A_6	3,612.50	1	3,612.50	2.64
A_7	1,512.50	1	1,512.50	1.11
A_8	1,512.50	1	1,512.50	1.11
A_9	112.50	1	112.50	0.08
A_{10}	2,812.50	1	2,812.50	2.06
A_{11}	9,800.00	1	9,800.00	7.16**
A_{12}	122,512.50	1	122,512.50	89.55**
Between H at M_2A_1	90,312.50	1	90,312.50	66.02**
A_2	57,800.00	1	57,800.00	42.25**
A_3	43,512.50	1	43,512.50	31.81**
A_4	57,800.00	1	57,800.00	42.25**
A_5	32,512.50	1	32,512.50	23.77**
A_6	28,800.00	1	28,800.00	21.05**
A_7	12,800.00	1	12,800.00	9.36**
A_8	19,012.50	1	19,012.50	13.90**
A_9	9,112.50	1	9,112.50	6.66**
A_{10}	6,050.00	1	6,050.00	4.42*
A_{11}	35,112.50	1	35,112.50	25.67**
A_{12}	72,200.00	1	72,200.00	52.78**
Within cell	1,969,949.90	1,440	1,368.02	

Note. H = hearing condition; M_1 = head fixed, M_2 = head rotate; A_1 to A_{12} = azimuth level.

*$p < .05$.

**$p < .01$.

accurate. But under the head rotate condition the binaurals were superior at these azimuths. At -30° there was no difference between the groups for the head fixed condition at A10, but binaurals were superior for head rotate at all azimuths.

The main effect of head movement, i.e., significantly smaller error scores when subjects' heads were free to rotate (M = 32.77) than when fixed in place (M = 44.06), was modified by the significant Azimuth x Head Movement interaction (see Figure 12 and Table 10). Analysis of these profiles indicated that subjects had significantly larger error scores at A1, 4, 5, 6, 7, and 12 for the head fixed than for the head rotate condition, with a significant reversal occurring at A9. However, the significant Head Movement x Azimuth x Hearing Condition interaction (see Figure 11 page 115 for this profile pattern) qualified these effects. The simple Head Movement x Azimuth interaction at the monaural level was significant, F (11, 660) = 4.46, p < .01, and simple simple main effects tests indicated that monaurals had significantly smaller error scores at azimuths A1, 5, 6, 7, and 12 for head rotate than for head fixed (see Table 11). At A9, as was seen in the Head Movement x Azimuth interaction, this trend reversed, with head rotation significantly decreasing localization accuracy. The simple interaction was also significant at the binaural level, F (11, 660) = 4.55, p < .01. And Table 11 shows that at A1, 5, 6, and 7, head fixation error scores were significantly larger than those for head rotation. Examination of the simple Head Movement x Azimuth interaction for binaurals with respect to azimuth revealed that binaurals allowed rotation performed equally well at all 12 azimuths (see Table 12). This was not the case, however, for

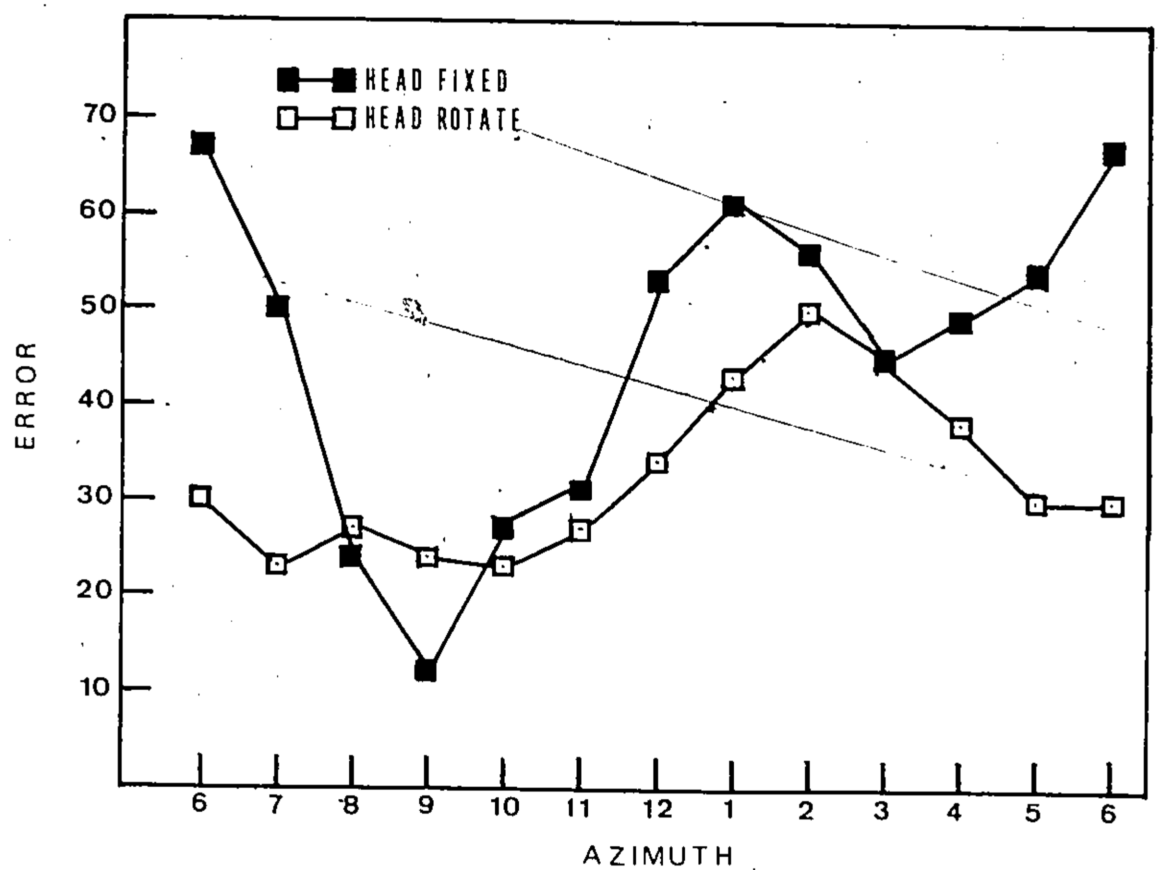

Figure 12. Mean error in degrees as a function of azimuth (clock-code) and head movement.

Table 10

Analysis of Variance for Simple Effects of Head Movement for the Azimuth x Head Movement Interaction

Source	SS	df	MS	F
Within subjects				
Between M at A_1	11,556.25	1	11,556.25	10.55**
A_2	1,225.00	1	1,225.00	1.12
A_3	25.00	1	25.00	0.02
A_4	4,556.25	1	4,556.25	4.16*
A_5	19,600.00	1	19,600.00	17.90**
A_6	49,506.25	1	49,506.25	45.22**
A_7	28,056.25	1	28,056.25	25.62**
A_8	400.00	1	400.00	0.37
A_9	4,900.00	1	4,900.00	4.48*
A_{10}	506.25	1	506.25	0.46
A_{11}	506.25	1	506.25	0.46
A_{12}	12,656.25	1	12,656.25	11.56**
P x subj. w. groups + PA x subj. w. groups.	788,325.00	720	1,094.90	

Note. M = head movement; A_1 to A_{12} = azimuth level.

*$p < .05$.

**$p < .01$.

Table 11

Analysis of Variance for Simple Simple Effects of Head Movement for the Head Movement x Azimuth x Hearing Condition Interaction

Source	SS	df	MS	F
Within subjects				
Between M at H_1A_1	5,512.50	1	5,512.50	5.03*
A_2	612.50	1	612.50	0.56
A_3	450.00	1	450.00	0.41
A_4	4,050.00	1	4,050.00	3.70
A_5	6,050.00	1	6,050.00	5.53*
A_6	10,512.50	1	10,512.50	9.60**
A_7	6,612.50	1	6,612.50	6.04*
A_8	4,050.00	1	4,050.00	3.70
A_9	8,450.00	1	8,450.00	7.72**
A_{10}	12.50	1	12.50	0.01
A_{11}	800.00	1	800.00	0.73
A_{12}	14,450.00	1	14,450.00	13.20**
Between M at H_2A_1	6,050.00	1	6,050.00	5.53*
A_2	612.50	1	612.50	0.56
A_3	200.00	1	200.00	0.18
A_4	1,012.50	1	1,012.50	0.92
A_5	14,450.00	1	14,450.00	13.20**
A_6	45,000.00	1	45,000.00	41.10**
A_7	24,200.00	1	24,200.00	22.10**
A_8	1,250.00	1	1,250.00	1.14
A_9	50.00	1	50.00	0.05
A_{10}	800.00	1	800.00	0.73
A_{11}	3,612.50	1	3,612.50	3.30
A_{12}	1,512.50	1	1,512.50	1.38
P x subj. w. groups + PA x subj. w. groups	788,325.00	720	1,094.90	

Note. M = head movement; H_1 = monaural, H_2 = binaural; A_1 to A_{12} = azimuth level.

*$p < .05$.

**$p < .01$.

Table 12

Analysis of Variance for Simple Simple Effects of Azimuth for the Head Movement x Azimuth x Hearing Condition Interaction

Source	SS	df	MS	F
Within subjects				
Between A at M_1H_1	292,973.00	11	26,633.91	21.30*
M_1H_2	86,891.67	11	7,899.24	6.32*
M_2H_1	108,075.00	11	9,825.00	7.86*
M_2H_2	12,191.67	11	1,108.33	0.89
A x subj. w. groups + PA x subj. w. groups	1,650,862.50	1,320	1,250.65	

Note. A = azimuth; M_1 = head fixed, M_2 = head rotate; H_1 = monaural, H_2 = binaural.

*$p < .01$.

any of the remaining combinations of hearing condition and head movement levels. The Head Movement x Azimuth x Hearing Condition interaction was itself influenced by the significant Head Movement x Azimuth x Hearing Condition x Elevation interaction. As the profiles in Figure 5, (page 96) illustrate, in general, monaurals benefited from head rotation to some degree at all elevations for azimuths on the occluded side, with the effect being most noticeable at -30°. Monaurals also showed a trend at each elevation for head rotation to increase error scores at azimuths 8 and 9. For binaurals, performance at $+30^{\circ}$ and 0° elevation for azimuths, 5, 6, and 7 was considerably improved by head rotation. At -30°, however, head rotation did not have as great an influence on accuracy. In fact, there was a slight reversal at A6, as there was at A2 for 0° and at A3 and A9 for $+30^{\circ}$, with head rotation producing larger error scores than head fixed. As Table 2 shows, the remaining main effect, azimuth, was significant (see Table 13 for means). Except for the simple simple main effect test discussed earlier, no other comparisons were made between the azimuth levels.[2]

Hypotheses Testing

Traditionally, a front-back or back-front reversal for monaural listeners has been considered an error of 180 degrees re the median plane (i.e., 0° azimuth) - for example, in this study, a subject's reporting A6 for A12 or A12 for A6, a front-back or back-front reversal, respectively. However, research by Butler and Naunton (1967) suggests this criterion may be too restrictive. They reported that untrained monaurals tended to perceive noise-bursts presented directly in front of them as offset up to 26 degrees (median score) towards the side of

Table 13

Mean Errors In Degrees as a Function of Azimuth

Azimuth											
1	2	3	4	5	6	7	8	9	10	11	12
51.88	52.92	45.00	43.13	42.08	48.54	36.46	25.42	17.92	25.21	28.96	43.54

the unoccluded ear. This finding suggests that a reversal, given the cone of confusion model, need not be limited to 180 degrees for monaurals, and for the present report will be defined as an error of 150 degrees or greater, i.e., reporting A5, 6 or 7 (front-back reversal) or, A11, 12 or 1 (back-front). This redefinition will be considered further in the discussion, but for readers interested in the 180° reversal results, those data are presented in Appendices B and C, which refer, respectively, to hypothesis 1 and 2.

To test hypothesis 1, that trained monaurals with fixed heads will have fewer front-back reversals than trained binaurals with fixed heads, the number of reversals at azimuth 12 for each group were totalled over elevations (each elevation having 6 monaural and 6 binaural subjects) and compared using the Fisher exact probability test.[3] The hypothesis was not supported. In fact, the direction of the difference was opposite to that predicted: The number of monaurals who made reversals at A12 (6 out of 18) differed significantly, $p < .05$ from the number of binaurals (0 out of 18). Examining the reversals at each elevation using Fisher exact tests revealed no significant differences, all $ps > .05$ (see Table 14 for data concerning hypothesis 1). An a posteriori, Chi-square analysis of the back-front reversals collapsed over elevation indicated there was no significant difference, $X^2 = 0$, $df = 1$, ns, monaurals having 5 reversals, binaurals 4. And for each elevation no significant differences were found (Fisher exact tests, all $ps > .05$).

Hypothesis 2, that trained monaurals with fixed heads will not differ significantly with respect to front-back reversals from trained or untrained binaurals allowed head movements, was tested using Fisher

Table 14

Number of Reversals ≥ 150 Degrees by Trained Monaurals and Binaurals With Fixed Heads

Reversal type	Total[a]	Elevation[b] +30°	0°	−30°
Front-back				
Monaurals	6	1	1	4
Binaurals	0	0	0	0
Back-front				
Monaurals	5	1	0	4
Binaurals	4	1	3	0

[a]Maximum total = 18.

[b]Maximum per elevation = 6.

exact probability tests, the data analyzed being the number of reversals $\geq 150^{\circ}$. Contrary to the prediction, the monaurals had significantly more confusions at azimuth 12 (6) than the trained binaurals (0), $p < .05$. However, the difference at each elevation was not significant, $ps > .05$ (see Table 15 for data concerning hypothesis 2). The difference in the number of back-front confusions was also nonsignificant, $p > .05$, with monaurals having 5, trained binaurals one. (Note: This binaural reversed 150°; removing this score produced a significant difference, Fisher exact test, $p < .05$.) There was no significant difference at specific elevations, all $ps > .05$.

Examining hypothesis 2 with respect to the untrained binaurals indicated the results were identical to those for the trained binaurals (see Table 15).

To summarize, then, significantly more monaurals had front-back confusions compared to either trained or untrained binaurals, but there were no significant differences for the back-front comparisons.

Hypothesis 3, predicting that trained monaurals with fixed heads will perform as well on the localization task at all elevations as trained binaurals with fixed heads, was not supported. Collapsing over azimuths and comparing the two groups revealed that the monaurals had significantly larger error scores for all elevations: +30 degrees, $F\ (1, 120) = 11.51$, $p < .01$, (Ms = 48.75 and 19.58); 0 degrees, $F\ (1, 120) = 14.30$, $p < .01$, (Ms = 55.41 and 22.91); -30 degrees, $F\ (1, 120) = 24.93$, $p < .01$, (Ms = 65.41 and 22.50).[4]

The prediction that trained monaurals with fixed heads will be no more inaccurate on their occluded side than are trained binaurals with fixed heads (hypothesis 4) was not supported. As illustrated in

Table 15

Number of Reversals ≥ 150 Degrees by Head Fixed Monaurals With Training and Head Rotate Binaurals With and Without Training

Reversal type	Total[a]	Elevation[b] +30°	0°	-30°
Front-back				
Monaurals	6	1	1	4
Binaurals (trained)	0	0	0	0
Binaurals (untrained)	0	0	0	0
Back-front				
Monaurals	5	1	0	4
Binaurals (trained)	1	0	0	1
Binaurals (untrained)	1	0	0	1

[a] Maximum total = 18.

[b] Maximum per elevation = 6.

Figure 13, monaurals had significantly larger error scores than binaurals at A1, F (1, 1440) = 40.36, $p < .01$; A2, F (1, 1440) = 6.59, $p < .05$; A3, F (1, 1440) = 6.59, $p < .05$; A4, F (1, 1440) = 16.44, $p < .01$; A6, F (1, 1440) = 7.30, $p < .01$; and A12, F (1, 1440) = 61.47, $p < .01$. Only at A5 were the groups equally accurate, F (1, 1440) = 3.58, *ns*. A posteriori F tests indicated there were no significant differences between the groups at the remaining azimuths.

To test hypothesis 5, i.e., trained monaurals allowed head rotation will localize as well in the frontal quadrant as untrained binaurals allowed head rotation, the error scores of the two groups were collapsed over elevations and compared using two-tailed t tests having reduced degrees of freedom.[5] The hypothesis was not supported, monaural errors, with one exception, being significantly larger in this quadrant: For azimuth 11, t (17) = 4.11, $p < .001$, (*Ms* = 51.66 and 6.66); A12, t (17) = 3.84, $p < .01$, (*Ms* = 58.33 and 5.0); A1, t (17) = 3.61, $p < .01$, (*Ms* = 61.66 and 11.66); and A2, t (17) = 2.32, $p < .05$, (*Ms* = 48.30 and 23.33). At A10 the difference was nonsignificant, t (17) = 1.81, *ns*, (*Ms* = 31.66 monaural, 11.66 binaural).

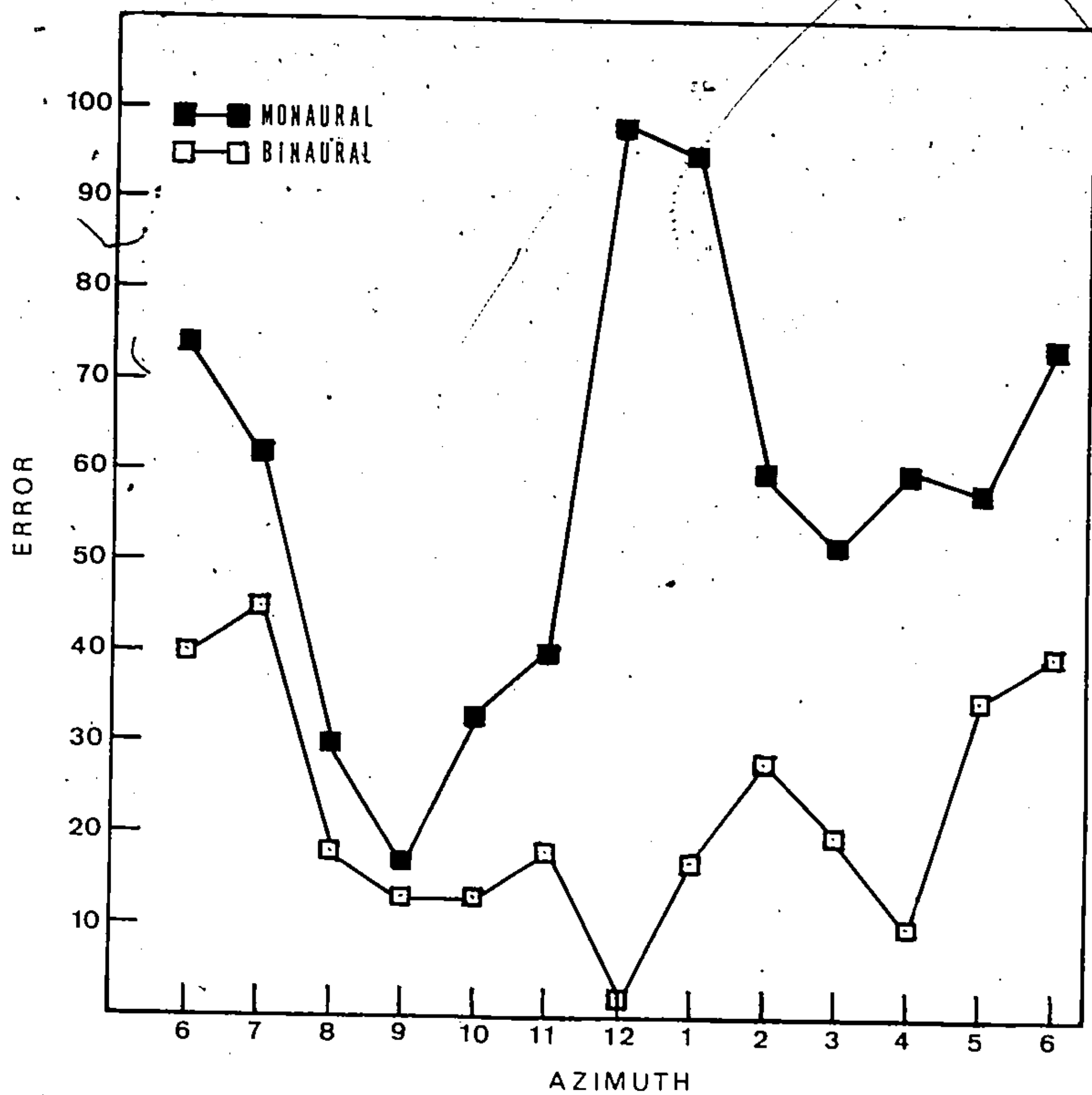

Figure 13. Mean error in degrees as a function of azimuth (clock-code) and hearing condition for trained subjects with fixed heads.

Chapter IV

Discussion

The overview of the results indicated that a number of the usual findings reported in the localization literature were confirmed by the present study. For example, monaurals performed poorly on their occluded side, and head movement improved binaural performance in the rear quadrant. But not all the results were typical of earlier reports. In particular, (1) head movement was found to decrease accuracy at some azimuths for both monaural and binaural listeners, and (2) untrained monaurals could often match binaural performance on the side of the non-occluded ear.

Rather than examine these atypical findings now, however, in order to consolidate the discussion, they will be considered later in conjunction with the hypothesis with which they share a similar theme. But two other statements from the overview are of immediate interest. The first--binaural listeners free to rotate their heads had the smallest error scores, and these scores were essentially independent of azimuth--supports Wallach's (1939) theorizing that head movements are an important component for accurate sound localization. In addition, this finding confirms a similar report made by Freedman and Fisher (1968) who also examined the localization of sound sources positioned around the subject at the level of the interaural axis. As the Head Movement x Azimuth x Hearing Condition x Elevation (M x A x H x E) interaction indicated, however, the advantage of head rotation is not limited to just this axis. It is clear from the interaction that sources located 30° above or below ear level are, with a few exceptions that will be discussed later, localized at least as accurately, if not more so, with head movement. Even though head rotation considerably improved rear quadrant localization at 0° elevation, it is also important to consider that the advantages of movement noted in this study do not in any general way contradict the findings of Jongkees and Veer (1958b). They reported (see page 37 of the present study) that in the frontal quadrant, there was no significant difference in the performance of subjects localizing with or without head movement. Re-examining the simple effects tests for the Head Movement x Azimuth x Hearing Condition (M x A x H) interaction outlined in Table 11 (page 120) shows that except for azimuth 1, the present results are in agreement with their finding.

It may be speculated on the basis of these data that because the head must be turned in order to visualize rear quadrant sound sources, the percept(s) of sound direction for that quadrant have developed on the basis of a dynamic cue system; whereas, in the frontal region, head movement is generally unnecessary for viewing a source, and understandably the percepts have developed on the basis of a relatively static cue system. Given such a system, restricting head movement will, of course, debilitate performance in the rear quadrant, the area where percepts are based on "moving" input. But error size should not increase significantly in the front where localization cues must match a "static engram". However, why the deficits should be most noticeable at $+30^{\circ}$ and 0° and less so at -30°, is not readily explainable.

The second overview statement--that for binaurals, training made no significant improvement in accuracy in any quadrant--provides base line data on an issue, i.e., the influence of training on binaural localization performance, which, as was mentioned earlier (page 48), has been neglected in the experimental literature. Questions such as the following--can binaural accuracy be improved? and if so, are there benefits to be gained in a nonexperimental setting, e.g., industry, from more accurate sound localization?--need to be considered. Certainly the present study suggests that limited training does not appear sufficient for obtaining significant gains. Perhaps new localization strategies must be taught if normal listeners are to increase their accuracy.

The failure of hypothesis one to be substantiated brings into question Fisher and Freedman's (1968a) finding that binaurals may have up to three times as many front-back reversals as binaurals, a finding central to those authors' argument that binaural cues are neither necessary nor sufficient for adequate auditory localization. A scenario can be envisaged, however, which reconciles the findings of the present study with the Fisher and Freedman (1968a) results. Recall the suggestion made earlier that a reversal for untrained monaurals should be considered an error of 150° or greater. This criterion was based on Butler and Naunton's (1967) finding that untrained monaurals tended to perceive noise-bursts presented directly in front of them as offset up to 26° (median score) towards the side of the unoccluded ear. With such a subjective bias, then, one reasonable location to expect a front-back reversal to fall would be on a circle of identity at approximately 15° to 26° to the side of the unoccluded ear at the rear (180°) pole--to the nearest azimuth, a 150° error in terms of the present study. There may be a question here of how the training received by the monaurals in the present study affected the proclivity to offset a centered stimulus. Perhaps the most convincing evidence that the limited training did not affect this bias is the observation that of the remaining 12 monaurals who did not reverse, none correctly identified position 12, with 9 of these 12 perceiving the stimulus nearer the side of the unoccluded ear. It can be assumed, then, that the monaurals making reversals were behaving much as the cone of confusion theory would predict; that is, they were confusing a front offset stimulus with a back offset stimulus. If this ex post facto argument advocating a 150° error criterion is accepted, then the 180° criterion used by Fisher and Freedman (1968a) should also be re-examined to ensure that the total number of reversals recorded for their monaurals has not been unwittingly reduced. Such a re-examination appears justified if there is a possibility that monaurals in that study, in spite of their apparent high degree of training, still confused the front and rear poles without making an objective error of 180°. One design feature of the Fisher and Freedman (1968a) study lends credence to this speculation: The sound pressure level of the stimulus was set at Reiz Limen for each monaural, suggesting that 50% of the time the subject was hearing the signal through his or her occluded ear. Under such test conditions three outcomes for the highly trained monaurals appear likely: (1) they perceived the front and rear poles in the objectively correct locations but simply made a front-back confusion, (2) they perceived the frontal sound as being off to the unoccluded ear side of the frontal pole and reversed to a comparable position on the circle of identity, and (3) they heard the sound through the monaural ear and confused front with back, a reversal not necessarily being 180° in this case. All three cases could conceivably appear in the behavior of one subject, but much remains to be investigated before the relevancy of these outcomes can be assessed. Similarly, to predict what effect leakage into the occluded ear will have on reversals with respect to the side of error, error size, and frequency requires a better understanding of the variables, both psychological and physical, influencing front-back confusion than is presently possessed. Nevertheless, these issues notwithstanding, if it is accepted that 180° need not be the only monaural reversal criterion in the Fisher and Freedman (1968a) study (their sound sources were separated by 22.5°, allowing a reversal to be 157.5° or greater), then the totals change somewhat: The monaurals made 9 reversals (an additional 4 over the sum for the 180° criterion) versus the binaural 16, a result still favoring the monaurals, but not as convincing a difference as the 16 to 5 comparison stressed by the authors.

With the two studies equated in this way, it should be recalled that Burgher's (1958) study using offset, front-back sources produced results in agreement with those of the present report: untrained monaurals with fixed heads had more reversals than untrained binaurals with fixed heads. An additional point should also be made here. Gatehouse and Cox (1972) reported that their binaurals made five times as many front-back reversals as the monaurals, agreeing therefore with Fisher and Freedman's findings. Unfortunately, Gatehouse and Cox's data are not reported in sufficient detail to be examined in terms of the modified reversal definition; consequently this discussion will deal with only the Fisher and Freedman report.

At this point in the scenario, two suppositions can be made. First, it is suggested that as monaural training increases, the number of 180° reversals increases with a concomitant decrease in 150° reversals. This speculation follows from the results of the present study where only 1 of the 6 monaural reversals was 180° compared to Fisher and Freedman's (1968a) report of 5 out of 9. Secondly, it is suggested there is also an overall decrease in the total number of monaural front-back confusions. Although the results of these two experiments cannot be convincingly extrapolated to these conclusions, the Searle, Braida, Davis, and Colburn (1976) model for auditory localization implies such an outcome; that is, the model assumes a handicap (e.g., monaurality) can be alleviated by abnormal conditions (e.g., training). Specifically, the fine-tuning of a monaural subject to subtle front-back spectral differences seems a likely accomplishment following adequate training.

To continue with the scenario, it may be that the procedure used in providing this adequate training is a cause of the major conceptual discrepancy between the present front-back reversal results and those of Fisher and Freedman, that being the unexpected superiority of the monaurals over binaurals in the Fisher and Freedman study when the results of the present report and others, e.g., Perrott and Elfner (1968), would suggest that monaural reversals would simply match binaural. There appear to be two likely reasons for this discrepancy. First, Fisher and Freedman do not provide any details concerning the number of training trials administered nor the criterion which they adopted. If either of these procedures favored the monaurals, e.g., more trials on the occluded side or more training at all azimuths, then training bias (leading to confounding) becomes an issue, and superior monaural reversal performance could be anticipated according to the Searle et al. model. If confounding did occur it is impossible, of course, to decide whether trained monaurals are inherently superior to trained binaurals in eliminating front-back confusions or, alternatively, whether the superior training the monaurals received simply brought the number of reversals closer to an anticipated basement effect (i.e., zero reversals). The former possibility is Fisher and Freedman's thesis, but the latter may be equally likely.

The second reason raises a problem which must always be considered when subjects are administered multiple treatments; that is, the influence of nonlinear (differential) carry-over effects. Even though Fisher and Freedman counterbalanced the monaural versus binaural order for their subjects (hearing condition being a within subject variable), this method does not control for nonlinear carry-over (Christensen, 1977). It is quite possible that for the monaural to binaural sequence, the experience of having been monaural first gives rise to confusions for binaurals at certain azimuths--e.g., stimuli directly in front or behind where there is always some degree of ambiguity even under ideal conditions; cf., stimuli at 90° and 270° which are rarely reversed--confusions due to the "image" retained from the monaural condition (an image, as was mentioned earlier, sometimes monaural at others binaural) competing with the binaural cues. Whereas in the binaural to monaural sequence, the monaurals simply adjusted to the new set of cues, there being no competing responses from the previous condition. Instead, the monaurals had to contend with sound leakage into the occluded ear; but this, it is suggested, does not increase their reversal scores, rather it forces us to question the appropriateness of a 180° reversal criterion.

To conclude this scenario, it should be noted that a discrepancy appears between the results of these two studies which admits to no obvious explanation: Why do the trained binaurals with fixed heads in the present study make only back-front confusions, when in the Fisher and Freedman report they make only front-back? Are, for example, the acoustic characteristics of the test chamber or the location of the experimenter during instructions and testing of importance in creating such discrepancies? Another unanswered question is whether the elevation of the sound source influences the number of reversals. There were, for example, in the present study more monaural reversals at -30° elevation than at the remaining two elevations. Is this a reliable trend or simply a chance result? If mathematical models are to be constructed which adequately mirror the localization process these questions must be answered using well designed studies having multiple factors.

With a monaural reversal considered, as argued previously, as an error of 150° or greater, the failure of hypothesis 2 to be supported is not surprising, in retrospect, given the absence of front-back reversals for trained binaurals with fixed heads and the use of the same monaural reversal totals for hypotheses 1 and 2. Understandably, this basement effect was unlikely to disappear with the addition of head rotation, when it is remembered that for the most part the literature suggests that front-back confusions decrease with head movement (Burger, 1958; Thurlow & Runge, 1967). Of somewhat more interest was the decrease in the number of back-front confusions which was evident upon comparing the head fixed (4 reversals) and head rotate (1) conditions for the trained binaurals. Although, neither total differed significantly from its monaural comparison, the decrease in reversals across head positions was in the right direction, a finding consistent with the reversal literature just cited. Unfortunately, a more convincing test of hypothesis 2 must await confirmation of the appropriateness of the predictions made earlier regarding subject training and experimental design for the Fisher and Freedman (1968a) study.

The failure of the results to support hypothesis three, even at elevation zero, was unexpected. But the results of the a posteriori interaction analysis, specifically the Azimuth x Hearing Condition x Training (A x H x T) interaction, provide the obvious explanation for the lack of consistency between the present results and those of Fisher and Freedman on which the prediction was based. The training variable simply did not include a representative series of levels (assuming, that the Fisher and Freedman findings can be replicated when the methodology of that study is altered as suggested). However, because hypothesis 3 makes no prediction concerning the influence of azimuth on localization behavior, the discussion of the A x H x T interaction will be pursued, more appropriately, later during the examination of hypothesis 4. What is of interest here is that the failure of the data to support hypothesis 3 is consistent with the findings of Batteau (1968) and Gatehouse and Cox (1972) who also found that when only the hearing condition variable was considered, binaurals outperformed monaurals on horizontal localization. To elaborate on this point somewhat, it will be recalled that the nonsignificant Head Movement x Hearing Condition x Elevation x Training interaction was used to test hypothesis 3 and that the influence of hearing condition on localization accuracy was not qualified by any combination of either elevation, training, or head movement, the same three variables which Batteau (1968) and Gatehouse and Cox (1972) either collapsed over, failed to control, or found did not influence their results. Apparently, then, the manipulation of these variables in the present study was adequate to replicate the conditions present in those two studies. And although the present study does not unequivocally reconcile the opposing findings of the Fisher and Freedman (1968a) versus the Batteau, and the Gatehouse and Cox reports, the presence of interactions, such as the A x H x T, reveals an obvious nexus between these three studies, a connection which makes unqualified statements concerning monaural versus binaural performance appear misguided.

Although the data failed to support hypothesis 4, except at azimuth 5, the A x H x T and Head Movement x Azimuth x Hearing Condition x Training (M x A x H x T) interactions indicate that the results are in the direction predicted and are therefore consistent with the Fisher and Freedman findings from which the hypothesis emanated. Because the analysis of the M x A x H x T interaction was limited to only one level of the training variable, i.e., subjects with training, the A x H x T interaction will be used in discussing this conclusion concerning the suggested agreement between the two studies. However, the training/no-training profiles for the M x A x H x T interaction have been examined and are similar to those of the A x H x T interaction. Specifically, Figure 6 (page 97), depicting the A x H x T interaction, shows clearly that although the monaurals are still inferior at localizing on the occluded side, even after receiving some training, the monaural versus binaural difference has decreased noticeably from the no-training condition, emphasizing the point made earlier that had more training trials been administered to some of the comparison groups, the monaurals may well have matched the binaurals' performance. It may even be speculated that the nonsignificant difference between the two hearing conditions at azimuth 5 in the M x A x H x T interaction may indicate that quadrant where this matching will first occur.

Considering the unoccluded side for comparison, the M x A x H x T interaction (Figure 13, page 129) indicated that except for azimuth 12 and 6, the difference between the monaurals and binaurals for the training condition was not significant, indicating, generally, that the Fisher and Freedman results for this side are consistent with those of the present study. Apparently, then, training (i.e., informing the subject of the appropriateness of his or her decision) is not the crucial variable influencing localization accuracy in these two quadrants, remembering that monaurals in the present study received only one training trial at each angle prior to testing. This conclusion can be further substantiated by examining the no-training profile of the A x H x T interaction (Figure 6, page 97). Here, we see again that with the exception of azimuths 6, 11 and 12, monaurals can perform with accuracy comparable to that of normal listeners. However, these results are not consistent with those of Russell (1976), who, it will be recalled (see page 70), did not train his subjects and yet found the overall binaural performance superior to monaural. Aside from the fact that Russell did not report whether any interactions had occurred, an issue of some concern according to the results of the present study, there are two apparent explanations for the lack of consensus between the three studies. First, in both the present study and Fisher and

Freedman's (1968a), the subjects were exposed to the signal at least once at each angle prior to testing; whereas, Russell appears to have tested his subjects without allowing them any preliminary exposure to the stimulus locations. His results may be accurately reflecting the initial difference between monaural and binaural performance for those situations where subjects are totally unfamiliar with the images created by sounds coming from the various azimuths--a situation where it may be expected that monaurals will do poorly even on their unoccluded side. This explanation follows from the reports of Angell and Fite (1901a, 1901b) who found monaurals improved their performance without knowledge of results by simply being allowed to practice the localization task.[6]

The second explanation concerns the procedure used in both this and the Fisher and Freedman (1968a) study of blindfolding the subject to eliminate visual cues rather than concealing the source (or sources) behind a screen. The latter procedure, which makes blindfolding unnecessary, was used by Russell. Blindfolding binaural subjects appears to have a debilitating influence on their localization accuracy according to the results of an unpublished study conducted by J. Rodger (Note 1) of Queen's University. He found that normal hearing subjects localized left-front quadrant sources significantly better when they could see the sound sources (identical speakers) than when they tried the same task while blindfolded, a finding which may reflect the binaural's inability to correctly perceive the orientation of his or her head over extended periods of time without visual confirmation. Rodger's results suggest that the binaurals in the present and the Fisher and Freedman study may have been negatively influenced by their lack of vision to a greater extent than the monaurals, thus making it "easier" for the monaurals to match binaural performance on the unoccluded side. That is, as localization in these two quadrants is generally more accurate than on the occluded side (Butler, 1975), a finding clearly evidenced in the present study, any procedure detrimental to binaurals would necessarily decrease the already relatively small difference between the two hearing conditions on this side. A similar study to that of Rodger's comparing the performance of sighted and blindfolded monaural and binaural subjects would provide an interesting comment on these speculations.

Although the results failed to support hypothesis 5, except at azimuth 10, the a posteriori interaction analyses clearly showed that in the front quadrant (1) training can increase monaural accuracy on the occluded ear side and (2) head rotation like training does reduce the monaural versus binaural difference at some azimuths. The appropriateness of these conclusions can be noted by examining the highest order interactions in which the two variables appear, i.e., A x H x T and Head Movement x Azimuth x Hearing Condition x Elevation (M x A x H x E), remembering that because training and head position did not interact, their effects on the dependent measure can be considered separately. As the influence of training on localization behavior in both the left and right front quadrants has been covered for the A x H x T interaction, only a few additional comments will be made here.

The decrease in the monaural versus binaural difference (i.e., performance of the two groups is becoming similar) from the no-training to training condition at azimuths 1 and 2 in the present study is consistent with the results of Bauer, Matuzsa, Blackmer, and Glucksberg (1966) and Perrott and Elfner (1968), which demonstrated that monaurals do improve their accuracy in the frontal quadrant with increased training. However, neither research group examined performance at individual azimuths over the course of training, making it impossible to determine if their monaurals early in the training regime improved more rapidly at azimuths on the occluded ear side than they did at frontal sources on the opposite side as was the case in the present study. In both these studies the subjects appear to have been well trained, i.e., Bauer et al. gave their monaurals a minimum of five hours of alternative rest and training sessions and Perrott and Elfner gave 40 training trials on a task involving only two azimuths ($\pm 45^{o}$), so the failure of training to improve performance on the non-occluded side in the present experiment is understandable. It may be speculated that the reason the limited training given in the present experiment produced a greater influence at azimuths 1 and 2 than at 10 and 11 was the result of the monaurals being made aware of certain characteristics of sounds coming from the occluded side, even though they may not have been able to verbalize what those characteristics were. For without this awareness (i.e., no-training condition) their <u>perception</u> of sound location would be theoretically limited to the open ear side, with a guess occasionally directed toward the occluded side. Indeed, as one subject remarked, "the sound can't always be coming from only one part of the circle". Whereas on the unoccluded side, the relatively subtle difference between sounds from adjacent sources would not become apparent with only minimal training. Nevertheless, localization at these frontal azimuths would be, as the A x H x T interaction indicates, more accurate than at azimuths 1 and 2 because the percept of the locus of the sound source and the actual location of the source could coincide here. This argument is based upon the assumption that artifically created monaurals do not perceive, as distinguished from deduce, sounds as coming from the plugged ear side unless they receive considerable training.

That head rotation can, in general, reduce the monaural versus binaural difference for sources at 0^{o} elevation in the frontal quadrant is evident from the profiles of the M x A x H x E interaction (Figures 4 and 5, pages 95 and 96, respectively), a result consistent with the findings of Aase (1962) and Butler, Naughton, Neff, and Strominger (1960). Only at position 11 was head rotation not of benefit, and, in fact, the difference between the two groups at this azimuth was greater than it was for the head fixed condition. This is the first study, to the author's knowledge, which has found such an effect, i.e., that head movement can be detrimental to monaural accuracy.

But as the findings indicated, position 11 was not the only location where reversals occurred. Rather than limit this discussion to the frontal quadrant, then, other azimuths and elevations will be considered here as well. Following that discussion, the nonsignificant main effect of elevation and the Elevation x Training (E x T) interaction will be examined. Then, the question of which cues (i.e., intra-aural amplitude or spectral differences) the monaural subjects were using to localize the stimulus will be considered, and finally some concluding remarks will be made.

The other locations where head rotation decreased monaural accuracy, and where this decrease in conjunction with an improvement (or slight decrease, but a smaller one than for monaurals) in binaural performance for the head rotate condition, had as a consequence the effect of increasing the monaural versus binaural difference relative to the head fixed reference were at azimuths 8 and 9 for elevation 0° and -30°, and 8, 9, 10, and 11 for elevation $+30^{\circ}$. At no elevation, then, were monaurals free from the negative influence of head rotation. At the remaining azimuths for each elevation, however, rotation tended to improve performance rather than have no effect.

Why these reversals should be limited to the area opposite the unoccluded ear, and more important why they should occur at all are questions which may have surprisingly simple answers. That is, allowing blindfolded monaurals to move their heads may simply leave them uncertain (owing to lack of visual feedback) of where straight ahead is, with the result being that they make their choices using an offset center. Of course decisions made under these circumstances are going to contain not only "pure" error, but also error resulting from the use of an inappropriate reference system. Whereas, with the head held stationary the monaural has a constant and appropriate grid on which to base his or her decision, and judgments of sound location will therefore contain only "pure" error. Because localization is relatively poor on the occluded side, even the loss of the appropriate reference system is overcome by the benefit of obtaining a better "look" via head rotation at sounds coming from that side. On the open side, however, localization is quite accurate without head movement (just as it was for the no-training condition) and creating an inaccurate reference system can only increase error scores.

What these answers suggest is that if monaurals can be tested in a localization paradigm which does not require blindfolding (screens or multiple speakers may be used), then error scores for sources opposite the unoccluded ear should not increase for the head rotate condition as they did in the present experiment. For in this case the monaurals would be able to visually confirm the poles of their reference grid during every head rotation.

The results also showed that a decrease in the monaural versus binaural difference for the head rotate condition occurred because of inferior binaural performance. At the three azimuths where this occurred, i.e., azimuth 3 at +30° elevation, A2 at 0°, and A6 at -30°, the decrease in the monaural versus binaural difference was due strictly to an increase in error size for binaurals, with the monaurals showing increased accuracy. At a fourth azimuth, 9 at +30°, the binaurals also had an increase in error score size, but not as great as the monaurals, the overall effect being a slight increase in the comparison difference.

Only one other study (Thurlow & Runge, 1967, see page 39 of the present study) has found that head rotation can negatively influence binaural accuracy. And in that study the subjects were also tested blindfolded. Thurlow and Runge reported, although they did not discuss the implications of the result, that at two azimuths, 10° left and 55° left of midline at elevations +41° and +32°, respectively, the subjects with fixed heads were more accurate localizers than either those subjects allowed only to rotate their heads or those allowed to rotate and pivot. At a third azimuth, 49° right of midline at +30° elevation, there was no difference between the head fixed and head rotate conditions; but for head rotate with pivot the head fixed condition was slightly superior.

The similarity in the results of the present and the Thurlow and Runge study, suggests that as was hypothesized for the monaural condition, for binaurals as well, head rotation without vision may create some degree of disorientation. Indirect support for this view comes from a debriefing comment made by some of the subjects. These listeners said they felt more confident of their choices when they did not have to move their head. However, it is not clear (1) why, if disorientation is the appropriate concern, the negative effects of head rotation should occur only at the frontal quadrants or at midline (either front or back) and (2) why, as in the case of the present report, the negative effects in the front quadrants disappear for elevation -30° to be replaced by the deficit at azimuth 6. Perhaps where intensity differences are greatest, i.e., in the area bordering 90° and 270° re the interaural axis (Feddersen, Sandel, Teas, & Jeffress, 1957), head movements, despite Wallach's (1939) argument to the contrary, are not necessary and requiring a subject to make them may only create confusion. This speculation follows from the hypothesis advanced earlier that localization depends mainly on a static cue system for frontal sources and a dynamic one for rear. With respect to the second question, several studies, e.g., Burger (1958), Fisher and Freedman (1968b), Thurlow and Runge (1967), have shown that back-front accuracy can be improved by head movement, so the deficit at azimuth 6 remains difficult to explain. Indeed, as was noted in the overview, the surprisingly large deficits at azimuths 5, 6, and 7 for elevations $+30^{o}$ and 0^{o} in the present study (a finding also reported by Hochberg, 1966) are eliminated for the head rotate condition, a clear indication of the value of head movement in reducing confusions in that quadrant--at least at some elevations. Clearly, binaurals must be tested in a localization paradigm where vision is made a variable if the negative influence of head rotation is to be considered a normal feature of binaural localization and not just an artifact of the testing method.

An interesting result in the present study was the nonsignificant main effect for elevation. When it is recalled that the distance from the center of a subject's interaural axis to any one of the source elevations was constant (i.e, the speaker locations traced a sphere around the head), larger error scores at $\pm 30^{o}$ would be expected (and the trend was in this direction) given that the horizontal distance between sources decreases as the speaker is moved above or below the interaural axis, either location making the localization task more demanding. Smith (Note 2) has suggested an explanation for the nonsignificant result: The elevations used did not decrease the distance between adjacent sources to the extent required for the difference limen to be exceeded. For as Wallach (1940) has noted the cosine function of the angle of elevation changes relatively little from 0 to 30^{o}. Consequently, if at 0^{o} elevation, the distance between two adjacent speaker positions is, for example, 1 m, at 30^{o} elevation the value is 0.86 m; but for 60^{o} it will decrease to 0.50 meter. The question remains as to the elevation which must be used if the error scores are to differ significantly from those for the interaural axis.

The present results suggest the value may not need to be much greater, perhaps an elevation between 35° and 40°. It would be instructive to compare the nonsignificant main effect of elevation with the results of other studies. Unfortunately such comparisons cannot be made because researchers, for example, Gatehouse and Cox (1972), typically use elevation as a dependent variable; whereas, in the present experiment, it was treated as independent variable.

Although elevation did not produce a main effect, the results showed the variable did qualify the main effect of training, i.e., the E x T interaction. This too is a rather interesting effect in that all the remaining first-order interactions involve the variable, azimuth. There is no obvious reason why training did not decrease error scores at -30° and 0°, as it did at +30°. Certainly, if in addition to +30°, training had also increased localization accuracy at -30°, the interaction would be more readily understandable. For in this case, the localization of sources above and below the interaural axis could be viewed as a somewhat novel event for the subjects, compared with the more normal situation of localizing sources at approximately head level, and training would be expected to have a positive effect. Accepting this argument, the results suggest that localizing sources at +30° is the more demanding task, although why this should be so is unclear.

The replies of the monaural subjects during the debriefing to questions concerning what it was about the sound stimulus which helped them decide its location were quite similar. The most frequent comment was that the sound was "louder" or had a "loud volume" on the open ear side and was either "fainter" or "softer" on the occluded. Some subjects used the words "farther away" or "distant" to describe sounds on the occluded side, and occasionally the phrases "I had a feeling" or "it was clear on the open side" were mentioned. These replies suggest that intra-aural amplitude difference was the cue most likely being used by the monaurals, a result which is consistent with the interpretation that Gatehouse and Cox (1972) placed on their findings. However, the structuralist approach used in the present study for obtaining feedback from the monaurals is open to all the criticisms which are typically raised against introspective methods. Studies like that of Perrott and Elfner (1968) who found similar results using a behavioristic approach are, of course, to be preferred. Nevertheless, the results of the present study lend some support to the view that monaurals, who have not had special training, decide sound direction on the basis of loudness differences and not timbre differences.

In conclusion, the results of this study indicate that unqualified statements concerning monaural versus binaural accuracy and unqualified statements concerning the effects of training and head movement on localization performance are misleading. The presence of second and third-order interactions indicates that accurate sound localization depends on a number of factors; the manipulation of variables and the design of studies should reflect this. It is further suggested that multivariate studies such as the present one more accurately reflect the task demands of localization in the natural hearing environment.

Footnotes

[1]The Head Movement x Azimuth x Hearing Condition x Elevation interaction will be statistically analyzed for presentation in a coming report on this study.

[2]At the time of this analysis, there were no theoretical considerations connected with this dissertation necessitating such comparisons.

[3]The Fisher exact probability test was used when an expected frequency was less than 4.5; the chi-square test, corrected for continuity, when an expected frequency was $\geq$ 4.5.

[4]These simple simple main effects test results, along with those used in testing hypothesis 4, are based on the ANOVA results outlined in the previous section.

[5]Because the assumption of homogeneity of variance was violated, the *t* tests were conducted using one-half the normal degrees of freedom as recommended by Downie and Heath (1970, p. 185).

[6]Future analysis planned for the untrained monaurals' first 12 trials in the present study will provide additional information on this issue.

APPENDIX A

Total Error in Degrees For Trained and Untrained Monaurals and Binaurals at Elevations +30, 0, and -30^{o}

Condition[a]	Azimuth[b]											
	1	2	3	4	5	6	7	8	9	10	11	12
Head Fixed												
Monaural (T)												
$+30^{o}$	390	270	360	300	180	360	450	180	30	180	330	480
0^{o}	780	570	330	300	360	300	300	180	90	120	120	540
-30^{o}	540	240	240	480	510	660	360	180	180	300	270	750
Monaural (NT)												
$+30^{o}$	630	720	750	660	720	450	240	210	30	180	240	450
0^{o}	540	660	540	540	270	330	240	90	90	300	240	570
-30^{o}	570	570	450	630	480	570	390	180	60	120	330	600
Binaural (T)												
$+30^{o}$	90	210	120	60	150	180	240	180	90	60	30	0
0^{o}	90	60	90	60	270	540	300	90	30	30	60	30
-30^{o}	120	240	150	60	210	0	270	60	120	150	240	0
Binaural (NT)												
$+30^{o}$	240	240	60	180	300	540	420	210	60	150	180	210
0^{o}	60	60	60	120	270	720	300	90	60	60	90	0
-30^{o}	330	180	120	120	150	180	120	60	30	300	90	180

APPENDIX A-(Continued)

Condition[a]	Azimuth[b] 1	2	3	4	5	6	7	8	9	10	11	12
						Head Rotate						
Monaural (T)												
$+30^o$	480	270	180	180	150	330	180	330	90	120	390	420
0^o	270	270	330	300	240	30	180	300	300	90	180	240
-30^o	360	330	240	330	270	450	210	300	180	360	360	390
Monaural (NT)												
$+30^o$	540	750	690	750	480	450	270	180	270	330	270	480
0^o	570	690	600	390	360	210	240	120	240	180	390	510
-30^o	600	510	450	420	360	330	210	330	180	90	180	330
Binaural (T)												
$+30^o$	30	150	120	30	30	0	90	60	90	90	0	0
0^o	30	90	90	0	0	30	90	30	30	60	0	0
-30^o	0	120	120	90	90	150	0	0	90	150	60	0
Binaural (NT)												
$+30^o$	60	150	270	90	60	0	30	180	150	90	60	60
0^o	90	120	60	30	60	0	60	30	30	30	0	0
-30^o	60	150	60	90	90	180	60	90	60	90	60	30

[a]T = training, NT = no-training

[b]Each entry is the total error for 6 subjects.

APPENDIX B

Number of 180 Degree Reversals by Trained Monaurals and Trained Binaurals With Fixed Heads

Reversal type	Total[a]	Elevation[b]		
		$+30^{\circ}$	0°	-30°
Front-back				
Monaurals	1	0	0	1
Binaurals	0	0	0	0
Back-front				
Monaurals	0	0	0	0
Binaurals	4	1	3	0

Note: All comparisons were nonsignificant at the .05 probability level.

[a]Maximum total = 18.

[b]Maximum per elevation = 6.

APPENDIX C

Number of 180 Degree Reversals by Head Fixed Monaurals With Training and Head Rotate Binaurals With and Without Training

		Elevation[b]		
Reversal type	Total[a]	$+30^{o}$	0^{o}	-30^{o}
Front-back				
Monaurals	1	0	0	1
Binaurals (trained)	0	0	0	0
Binaurals (untrained)	0	0	0	0
Back-front				
Monaurals	0	0	0	0
Binaurals (trained)	0	0	0	0
Binaurals (untrained)	1	0	0	1

Note. All comparisons were nonsignificant at the .05 probability level.

[a]Maximum total = 18.

[b]Maximum per elevation = 6.

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